PCT

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G01B 9/02	A1	(11) International Publication Number: **WO 99/42787** (43) International Publication Date: 26 August 1999 (26.08.99)

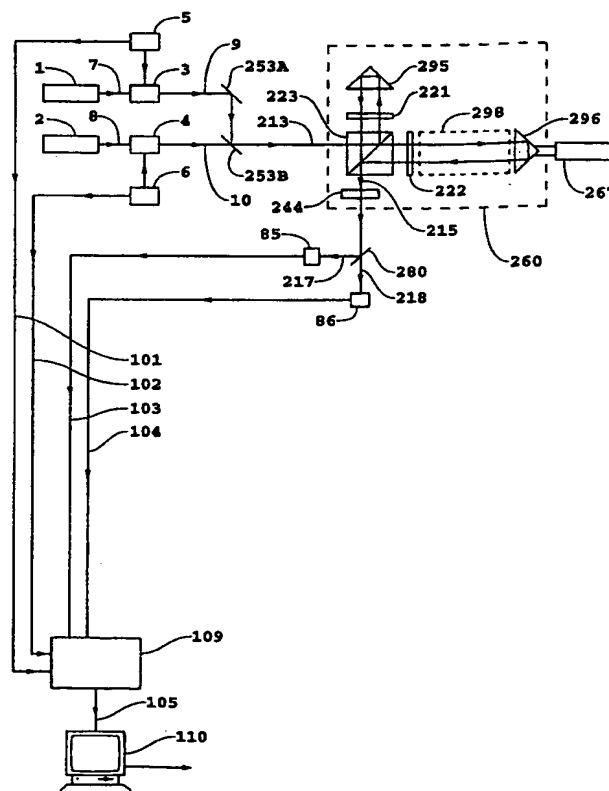|	

(21) International Application Number: PCT/US99/03554
 	
(22) International Filing Date: 18 February 1999 (18.02.99)
 	
(30) Priority Data:
    60/075,586   23 February 1998 (23.02.98)   US
    09/078,254   13 May 1998 (13.05.98)   US
 	
(71) Applicant: ZYGO CORPORATION [US/US]; Laurel Brook Road, Middlefield, CT 06455–0448 (US).
 	
(72) Inventors: DE GROOT, Peter; 355 Laurel Grove Road, Middletown, CT 06457 (US). HILL, Henry, A.; 340 South Avenida de Palmas, Tucson, AZ 85716 (US). DEMAREST, Frank, C.; 315 East Ridge Road, Middletown, CT 06457 (US).
 	
(74) Agent: CAUFIELD, Francis, J.; 6 Apollo Circle, Lexington, MA 02421–7025 (US).
	(81) Designated States: JP, KR, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).
	
	Published
	    With international search report.

(54) Title: INTERFEROMETER AND METHOD FOR MEASURING THE REFRACTIVE INDEX AND OPTICAL PATH LENGTH EFFECTS OF AIR

(57) Abstract

A method and apparatus for measuring fluctuations in the refractive index of a gas, such as air, in measurement path (298) comprising light sources (1) for providing two light beams (9, 10) with different wavelengths along the measurement path (298) of an interferometer (260) which are substantially harmonically related to each other and the output beams (103, 104) of the detectors (85, 86) are electronically processed by an electronic processor.

5

10   Title: INTERFEROMETER AND METHOD FOR MEASURING THE
                 REFRACTIVE INDEX AND OPTICAL PATH LENGTH EFFECTS
                 OF AIR

15

20

25

FIELD OF THE INVENTION

The present invention relates to optical instruments
for measuring distance and refractive index. The
30   invention relates in particular to interferometric
distance measurement independent of the optical path
length effects of refractive index of gas in a measurement
path including the effects of refractive index
fluctuations.

1

Background and Prior Art

A frequently-encountered problem in metrology is the
measurement of the refractive index of a column of air.
5   Several techniques exist for measuring the index under
highly controlled circumstances, such as when the air
column is contained in a sample cell and is monitored for
temperature, pressure, and physical dimension. See for
example, an article entitled "An air refractometer for
10 interference length metrology," by J. Terrien, *Metrologia*
1(3), 80-83 (1965).

Perhaps the most difficult measurement related to the
refractive index of air is the measurement of refractive
index fluctuations over a measurement path of unknown or
15 variable length, with uncontrolled temperature and
pressure. Such circumstances arise frequently in
geophysical and meteorological surveying, for which the
atmosphere is obviously uncontrolled and the refractive
index is changing dramatically because of variations in
20 air density and composition. The problem is described in
an article entitled "Effects of the atmospheric phase
fluctuation on long-distance measurement," by H. Matsumoto
and K. Tsukahara, *Appl. Opt.* **23**(19), 3388-3394 (1984), and
in an article entitled "Optical path length fluctuation in
25 the atmosphere," by G. N. Gibson *et al.*, *Appl. Opt.*
23(23), 4383-4389 (1984).

Another example situation is high-precision distance
measuring interferometry, such as is employed in micro-
lithographic fabrication of integrated circuits. See for
30 example an article entitled "Residual errors in laser
interferometry from air turbulence and nonlinearity," by
N. Bobroff, *Appl. Opt.* **26**(13), 2676-2682 (1987), and an
article entitled "Recent advances in displacement

2

measuring interferometry," also by N. Bobroff, *Measurement Science & Tech.* **4**(9), 907-926 (1993). As noted in the aforementioned cited references, interferometric displacement measurements in air are subject to

5   environmental uncertainties, particularly to changes in air pressure and temperature; to uncertainties in air composition such as resulting from changes in humidity; and to the effects of turbulence in the air. Such factors alter the wavelength of the light used to measure the

10   displacement. Under normal conditions the refractive index of air is approximately 1.0003 with a variation of the order of 1×10^{-5} to 1×10^{-4}. In many applications the refractive index of air must be known with a relative precision of less than 0.1 ppm (parts per million) to

15   0.003 ppm, these two relative precisions corresponding to a displacement measurement accuracy of 100 nm and 3 nm, respectively, for a one meter interferometric displacement measurement.

There are frequent references in the art to

20   heterodyne methods of phase estimation, in which the phase varies with time in a controlled way. For example, in a known form of prior-art heterodyne distance-measuring interferometer, the source emits two orthogonally polarized beams having slightly different optical

25   frequencies (*e.g.* 2 MHz). The interferometric receiver in this case is typically comprised of a linear polarizer and a photodetector to measure a time-varying interference signal. The signal oscillates at the beat frequency and the phase of the signal corresponds to the relative phase

30   difference. A further representative example of the prior art in heterodyne distance-measuring interferometry is taught in commonly-owned U.S. Pat. No. 4,688,940 issued to G. E. Sommargren and M. Schaham (1987). However, these

3

known forms of interferometric metrology are limited by
fluctuations in refractive index, and by themselves are
unsuited to the next generation of microlithography
instruments.

5   Another known form of interferometer for distance
measurement is disclosed in U.S. Pat. No. 4,005,936
entitled "Interferometric Methods And Apparatus For
Measuring Distance To A Surface" issued to J. D. Redman
and M. R. Wall (1977). The method taught by Redman and
10   Wall consists of employing laser beams of two different
wavelengths, each of which is split into two parts.
Frequency shifts are introduced into one part of the
respective beams. One part of each beam reflects from an
object and recombines with the other part on a
15   photodetector. From the interference signal at the
detector is derived a phase, at a difference frequency,
that is a measure of the distance to the surface. The
equivalent wavelength of the phase associated with the
difference frequency is equal to the product of the two
20   laser wavelengths divided by the difference of the two
wavelengths. This two-wavelength technique of Redman and
Wall reduces measurement ambiguities, but is at least as
sensitive to the deleterious effects of refractive index
fluctuations of the air as single-wavelength techniques.

25   Another example of a two-wavelength interferometer
similar to that of Redman and Wall is disclosed in U.S.
Pat. No.4,907,886 entitled "Method And Apparatus For Two-
Wavelength Interferometry With Optical Heterodyne
Processes And Use For Position Or Range Finding," issued
30   to R. Dändliker and W. Heerburgg (1990). This system is
also described in an article entitled "Two-Wavelength
Laser Interferometry Using Superheterodyne Detection," by
R. Dändliker, R. Thalmann, and D. Prongué, *Opt. Let.*

4

13(5), 339-341 (1988), and in an article entitled "High-
Accuracy Distance Measurements With Multiple-Wavelength
Interferometry," by R. Dändliker, K. Hug, J. Politch, and
E. Zimmermann.   The system of Dändliker *et al.*, as taught
5   in U.S. Pat. No.4,907,886, employs laser beams of two
wavelengths, each of the beams comprising two polarization
components separated in frequency by means of acousto-
optic modulation.   After passing these beams collinearly
through a Michelson interferometer, the polarization
10   components are mixed, resulting in an interference signal,
i.e. a heterodyne signal.   In that the heterodyne signal
has a different frequency for each of the two wavelengths,
a so-called superheterodyne signal results therefrom
having a frequency equal to the difference in the
15   heterodyne frequencies and a phase associated with an
equivalent wavelength equal to the product of the two
laser wavelengths divided by the difference of the two
wavelengths.   According to U.S. Pat. No. 4,907,886 (cited
above), the phase of the superheterodyne signal is assumed
20   to be dependent only on the position of a measurement
object and the equivalent wavelength.   Therefore, this
system is also not designed to measure or compensate for
the fluctuations in the refractive index of air.
      Further examples of the two-wavelength
25   superheterodyne technique developed by Redman and Wall and
by Dändliker and Heerburgg (cited above) are found in an
article entitled "Two-wavelength double heterodyne
interferometry using a matched grating technique," by Z.
Sodnik, E. Fischer, T. Ittner, and H. J. Tiziani, *Appl.*
30   *Opt.* **30**(22), 3139-3144 (1991), and in an article entitled
"Diode laser and fiber optics for dual-wavelength
heterodyne interferometry," by S. Manhart and R. Maurer,
SPIE **1319**, 214-216 (1990).   However, neither one of these

5

examples addresses the problem of refractive index
fluctuations.

It may be concluded from the foregoing that the prior
art in heterodyne and superheterodyne interferometry does
5   not provide a high speed method and corresponding means
for measuring and compensating the optical path length
effects of air in a measuring path, particularly effects
due to fluctuations in the refractive index of air. This
deficiency in the prior art results in significant
10   measurement uncertainty, thus seriously affecting the
precision of systems employing such interferometers as
found for example in micro-lithographic fabrication of
integrated circuits. Future interferometers will
necessarily incorporate an inventive, new method and means
15   for measuring and compensating a fluctuating refractive
index in a measurement path comprised of a changing
physical length.

One way to detect refractive index fluctuations is to
measure changes in pressure and temperature along a
20   measurement path and calculate the effect on the optical
path length of the measurement path. Mathematical
equations for effecting this calculation are disclosed in
an article entitled "The Refractivity Of Air," by F. E.
Jones, *J. Res. NBS* **86**(1), 27-32 (1981). An implementation
25   of the technique is described in an article entitled
"High-Accuracy Displacement Interferometry In Air," by W.
T. Estler, *Appl. Opt.* **24**(6), 808-815 (1985).
Unfortunately, this technique provides only approximate
values, is cumbersome, and corrects only for slow, global
30   fluctuations in air density.

Another, more direct way to detect the effects of a
fluctuating refractive index over a measurement path is by
multiple-wavelength distance measurement. The basic

principle may be understood as follows. Interferometers
and laser radar measure the optical path length between a
reference and an object, most often in open air. The
optical path length is the integrated product of the
5   refractive index and the physical path traversed by a
measurement beam. In that the refractive index varies
with wavelength, but the physical path is independent of
wavelength, it is generally possible to determine the
physical path length from the optical path length,
10   particularly the contributions of fluctuations in
refractive index, provided that the instrument employs at
least two wavelengths. The variation of refractive index
with wavelength is known in the art as dispersion,
therefore this technique will be referred to hereinafter
15   as the dispersion technique.

The dispersion technique for refractive index
measurement has a long history, and predates the
introduction of the laser. An article entitled "Long-Path
Interferometry Through An Uncontrolled Atmosphere," by K.
20   E. Erickson, *JOSA* **52**(7), 781-787 (1962), describes the
basic principles and provides an analysis of the
feasibility of the technique for geophysical measurements.
Additional theoretical proposals are found in an article
entitled "Correction Of Optical Distance Measurements For
25   The Fluctuating Atmospheric Index Of Refraction," by P. L.
Bender and J. C. Owens, *J. Geo. Res.* **70**(10), 2461-2462
(1965).

Commercial distance-measuring laser radar based on
the dispersion technique for refractive index compensation
30   appeared in the 1970's. An article entitled "Two-Laser
Optical Distance-Measuring Instrument That Corrects For
The Atmospheric Index Of Refraction," by K. B. Earnshaw
and E. N. Hernandez, *Appl. Opt.* **11**(4), 749-754 (1972),

7

discloses an instrument employing microwave-modulated HeNe
and HeCd lasers for operation over a 5 to 10 km
measurement path. Further details of this instrument are
found in an article entitled "Field Tests Of A Two-Laser
5   (4416A and 6328A) Optical Distance-Measuring Instrument
Correcting For The Atmospheric Index Of Refraction," by E.
N. Hernandez and K. B. Earnshaw, *J. Geo. Res.* **77**(35),
6994-6998 (1972). Further examples of applications of the
dispersion technique are discussed in an article entitled
10   "Distance Corrections For Single- And Dual-Color Lasers By
Ray Tracing," by E. Berg and J. A. Carter, *J. Geo. Res.*
85(B11), 6513-6520 (1980), and in an article entitled "A
Multi-Wavelength Distance-Measuring Instrument For
Geophysical Experiments," by L. E. Slater and G. R.
15   Huggett, *J. Geo. Res.* **81**(35), 6299-6306 (1976).

Although instrumentation for geophysical measurements
typically employs intensity-modulation laser radar, it is
understood in the art that optical interference phase
detection is more advantageous for shorter distances. In
20   U.S. Pat. No. 3,647,302 issued in 1972 to R. B. Zipin and
J. T. Zalusky, entitled "Apparatus For And Method Of
Obtaining Precision Dimensional Measurements," there is
disclosed an interferometric displacement-measuring system
employing multiple wavelengths to compensate for
25   variations in ambient conditions such as temperature,
pressure, and humidity. The instrument is specifically
designed for operation with a movable object, that is,
with a variable physical path length. However, the phase-
detection means of Zipin and Zalusky is insufficiently
30   accurate for high-precision measurement.

A more modern and detailed example is the system
described in an article by Y. Zhu, H. Matsumoto, T.
O'ishi, *SPIE* **1319**, Optics in Complex Systems, 538-539

8

(1990), entitled "Long-Arm Two-Color Interferometer For
Measuring The Change Of Air Refractive Index." The system
of Zhu *et al.* employs a 1064 nm wavelength YAG laser and
an 632 nm HeNe laser together with quadrature phase
5   detection. Substantially the same instrument is described
in Japanese in an earlier article by Zhu *et al.* entitled
"Measurement Of Atmospheric Phase And Intensity Turbulence
For Long-Path Distance Interferometer," Proc. 3rd Meeting
On Lightwave Sensing Technology, *Appl. Phys. Soc. of*
10   *Japan,* **39** (1989). However, the interferometer of Zhu *et*
al. has insufficient resolution for all applications, *e.g.*
sub-micron interferometry for microlithography.

     A recent attempt at high-precision interferometry for
microlithography is represented by U.S. Pat. No. 4,948,254
15   issued to A. Ishida (1990). A similar device is described
by Ishida in an article entitled "Two Wavelength
Displacement-Measuring Interferometer Using Second-
Harmonic Light To Eliminate Air-Turbulence-Induced
Errors," *Jpn. J. Appl. Phys.* **28**(3), L473-475 (1989). In
20   the article, a displacement-measuring interferometer is
disclosed which eliminates errors caused by fluctuations
in the refractive index by means of two-wavelength
dispersion detection. An Ar^{+} laser source provides both
wavelengths simultaneously by means of a frequency-
25   doubling crystal known in the art as BBO. The use of a
BBO doubling crystal results in two wavelengths that are
fundamentally phase locked, thus greatly improving the
stability and accuracy of the refractive index
measurement. However, the phase detection means, which
30   employ simple homodyne quadrature detection, are
insufficient for high resolution phase measurement.
Further, the phase detection and signal processing means
are not suitable for dynamic measurements, in which the

9

motion of the object results in rapid variations in phase
that are difficult to detect accurately.

In U.S. Pat. No. 5,404,222 entitled "Interferometric
Measuring System With Air Turbulence Compensation," issued
5   to S. A. Lis (1995), there is disclosed a two-wavelength
interferometer employing the dispersion technique for
detecting and compensating refractive index fluctuations.
A similar device is described by Lis in an article
entitled "An Air Turbulence Compensated Interferometer For
10   IC Manufacturing," *SPIE* **2440** (1995). Improvement on U.S.
Pat. No. 5,404,222 by S. A. Lis is disclosed in U. S. Pat.
No. 5,537,209, issued July 1996. The principal innovation
of this system with respect to that taught by Ishida in
Jpn. J. Appl. Phys. (cited above) is the addition of a
15   second BBO doubling crystal to improve the precision of
the phase detection means. The additional BBO crystal
makes it possible to optically interfere two beams having
wavelengths that are exactly a factor of two different.
The resultant interference has a phase that is directly
20   dependent on the refractive index but is substantially
independent of stage motion. However, the system taught
by Lis has the disadvantage that it is complicated and
requires an additional BBO crystal for every measurement
path. In that microlithography stages frequently involve
25   six or more measurement paths, and that BBO can be
relatively expensive, the additional crystals are a
significant cost burden. An additional disadvantage of
Lis' system is that it employs a low-speed (32-Hz) phase
detection system based on the physical displacement of a
30   PZT transducer.

It is clear from the foregoing, that the prior art
does not provide a practical, high-speed, high-precision
method and corresponding means for measuring refractive

index of air and measuring and compensating for the
optical path length effects of the air in a measuring
path, particularly the effects due to fluctuations in the
refractive index of the air. The limitations in the prior

5   art arise principally from the following unresolved
technical difficulties: (1) Prior-art heterodyne and
superheterodyne interferometers are limited in accuracy by
fluctuations in the refractive index of air; (2) Prior-art
dispersion techniques for measuring index fluctuations

10   require extremely high accuracy in interference phase
measurement, typically exceeding by an order of magnitude
the typical accuracy of high-precision distance-measuring
interferometers; (3) Obvious modifications to prior-art
interferometers to improve phase-measuring accuracy would

15   increase the measurement time to an extent incompatible
with the rapidity of stage motion in modern
microlithography equipment; (4) Prior-art dispersion
techniques require at least two extremely stable laser
sources, or a single source emitting multiple, phase-

20   locked wavelengths; (5) Prior-art dispersion techniques in
microlithography applications are sensitive to stage
motion during the measurement, resulting in systematic
errors; and (6) Prior-art dispersion techniques that
employ doubling crystals (e.g. U.S. Pat. No. 5,404,222 to

25   Lis) as part of the detection system are expensive and
complicated.

        These deficiencies in the prior art have led to the
absence of any practical interferometric system for
performing displacement measurement for microlithography

30   in the presence of a gas in a measurement path where there
are typically refractive index fluctuations and the
measurement path is comprised of a changing physical
length.

11

Accordingly, it is an object of the invention to provide a method and apparatus for rapidly and accurately measuring and monitoring the refractive index of a gas in a measurement path and/or the optical path length effects
5 of the gas wherein the refractive index may be fluctuating and/or the physical length of the measurement path may be changing.

It is another object of the invention to provide a method and apparatus for rapidly and accurately measuring
10 and monitoring the refractive index of a gas in a measurement path and/or the optical path length effects of the gas wherein the accuracy of measurements and monitoring of the refractive index of the gas and/or of the optical path length effects of the gas are
15 substantially not compromised by a rapid change in physical length of measurement path.

It is another object of the invention to provide a method and apparatus for rapidly and accurately measuring and monitoring the refractive index of a gas in a
20 measurement path and/or the optical path length effects of the gas wherein the method and apparatus does not require measurement and monitoring of environmental conditions such as temperature and pressure.

It is another object of the invention to provide a
25 method and apparatus for rapidly and accurately measuring and monitoring the refractive index of a gas in a measurement path and/or the optical path length effects of the gas wherein the method and apparatus may use but does not require the use of two or more optical beams of
30 differing wavelengths which are phase locked.

It is another object of the invention to provide a method and apparatus for rapidly and accurately measuring and monitoring the optical path length effects of a gas in

12

a measurement path wherein the lengths of measuring paths
in an interferometric measurement are substantially not
used in a computation of the optical path length effects
of the gas.

5   Other objects of the invention will, in part, be
obvious and will, in part, appear hereinafter. The
invention accordingly comprises methods and apparatus
possessing the construction, steps, combination of
elements, and arrangement of parts exemplified in the
10   detailed description to follow when read in connection
with the drawings.

                    SUMMARY OF THE INVENTION

15   The present invention generally relates to apparatus
and methods for measuring and monitoring the refractive
index of a gas in a measurement path and/or the change in
optical path length of the measurement path due to the gas
wherein the refractive index of the gas may be
20   fluctuating, e.g., the gas is turbulent, and/or the
physical length of the measuring path may be changing.
The present invention also relates to apparatus and
methods for use in electro-optical metrology and other
applications. More specifically, the invention operates
25   to provide measurements of dispersion of the refractive
index, the dispersion being substantially proportional to
the density of the gas, and/or measurements of dispersion
of the optical path length, the dispersion of the optical
path length being related to the dispersion of the
30   refractive index and the physical length of the
measurement path. The refractive index of the gas and/or
the optical path length effects of the gas are
subsequently computed from the measured dispersion of the

                           13

refractive index and/or the measured dispersion of the
optical path length, respectively. The information
generated by the inventive apparatus is particularly
suitable for use in interferometric distance measuring

5   instruments (DMI) to compensate for errors related to
refractive index of gas in a measurement path brought
about by environmental effects and turbulence induced by
rapid stage slew rates.

   Several embodiments of the invention have been made

10   and these fall broadly into two categories that address
the need for more or less precision in final measurements.
While the various embodiments share common features, they
differ in some details to achieve individual goals.

   In general, the inventive apparatus comprises

15   interferometer means having first and second measurement
legs at least one of which changes in length and at least
one of which is at least in part occupied by the gas.
Perferably a reference leg and a measurement leg are used
in preferred embodiments. The constituent legs are

20   preferably configured and arranged so that the measurement
leg has a portion of its optical path length substantially
the same as the optical path length of the reference leg.
The gas in the remaining portion of the optical path of
the measurement leg in a typical interferometric DMI

25   application is air.

   Means for generating at least two light beams having
different wavelengths are included. In preferred
embodiments, a source generates a set of light beams, the
set of light beams being comprised of at least two light

30   beams, each beam of the set of light beams having a
different wavelength. The relationship between the
wavelengths of the beams of the set of light beams, the
approximate relationship, is known.

A set of frequency-shifted light beams is generated
from the set of light beams by introducing a frequency
difference between two orthogonally polarized components
of each beam of the set of light beams such that no two
5   beams of the set of frequency-shifted light beams have the
same frequency difference. For a given embodiment, the
ratios of the wavelengths are the same as the known
approximate relationship to relative precisions which
depend on chosen operating wavelenghs and the
10   corresponding known approximate relationship. Because of
this wavelength dependence, these relative precisions are
referred to as the respective relative precisions of the
ratios of the wavelengths. In a number of embodiments,
the respective relative precisions of the ratios of the
15   wavelengths are of an order of magnitude less than the
respective dispersions of the gas times the relative
precision required for the measurement of the respective
refractive indices of the gas and/or for the measurement
of the respective changes in the optical path length of
20   the measurement leg due to the gas.

In certain ones of the embodiments, the approximate
relationship is expressed as a sequence of ratios, each
ratio comprising a ratio of low order non-zero integers,
e.g., 2/1, to respective relative precisions, the
25   respective relative precisions of the sequence of ratios,
wherein a respective relative precision of the respective
relative precisions of the sequence of ratios is of an
order of magnitude less than the respective dispersion of
the gas times the respective relative precision required
30   for the measurement of the respective refractive index of
the gas and/or for the measurement of the respective
change in the optical path length of the measurement leg
due to the gas.

15

In other embodiments, where the respective relative
precisions of the ratios of the wavelengths is
inappropriate to the desired value, means are provided for
monitoring the ratios of the wavelengths and either

5   providing feedback to control the respective relative
precisions of the ratios of the wavelengths, information
to correct subsequent calculations influenced by
undesirable departures of the respective relative
precisions of the ratios of the wavelengths from the

10 desired respective relative precisions of the ratios of
the wavelengths, or some combination of both. Means are
also provided for monitoring the wavelength used in the
primary objective of DMI, the determination of a change in
a length of the measurement path.

15   At least a portion of each of the frequency-shifted
light beams is introduced into the interferometer means by
suitable optical means so that a first portion of at least
a portion of each frequency-shifted light beam travels
through the reference leg along predetermined paths of the

20 reference leg and a second portion of at least a portion
of each frequency-shifted light beam travels through the
measurement leg along predetermined paths of the
measurement leg, the first and second portions of at least
a portion of each frequency-shifted light beam being

25 different. Afterwards, the first and second portions of
at least a portion of each frequency-shifted light beam
emerge from the interferometer means as exit beams
containing information about the optical path length
through the predetermined paths in the reference leg and

30 the optical path length through the predetermined paths in
the measurement leg.

Combining means are provided for receiving the exit
beams to produce mixed optical signals which contain

information corresponding to the phase differences between
the exit beams of the first and second portions of at
least a portion of each frequency-shifted light beam. The
mixed optical signals are then sensed by a photodetector,
5   preferably by photoelectric detection, which operates to
generate electrical interference signals that contain
information corresponding to the refractive index of the
gas at the different beam wavelengths and to the optical
path length in the measurement leg due to the refractive
10   index of the gas at the different beam wavelengths.

In certain of the embodiments, modified electrical
interference signals are then generated from the
electrical interference signals by either multiplying or
dividing the phase of each of the electrical interference
15   signals by a number, the relationship of the numbers being
either the same as the known approximate relationship of
the wavelengths or the same as the reciprocal of the known
approximate relationship of the wavelengths, respectively.

The electrical interference signals, or the
20   corresponding modified electrical interference signals
depending on the embodiment, are then analyzed by
electronic means that operate to determine the dispersion
of the optical path length of the measurement leg
substantially due to the dispersion of the refractive

25   index of the gas and/or the dispersion $\left(n_i - n_j\right)$ of the gas

where i and j are integers corresponding to wavelengths
and different from one another. From this information and
the reciprocal dispersive power of the gas, the

refractivity of the gas, $\left(n_r - 1\right)$ where r is an integer
30   corresponding to a wavelength, and/or the contribution to
the optical path length of the measurement leg due to the
refractive index of the gas can also be determined by the

17

electronic means. The value of *r* may be different from *i* and *j* or equal to either *i* or *j*. The electronic means can comprise electronic means in the form of a microprocessor or a general purpose computer suitably
5   programmed in well-known ways to perform the needed calculations.

In preferred form, the electrical interference signals comprise heterodyne signals containing phase information corresponding to the refractive index of the
10   gas and to the optical path length of the measurement leg and the apparatus further comprises means to determine the phases of the heterodyne signals to generate phase information corresponding to the dispersion of the refractive index of the gas and to the dispersion of the
15   optical path length of the measurement leg due to the dispersion of the refractive index of the gas. In certain of the embodiments, the apparatus further comprises means for mixing, *i.e.* multiplying, the modified heterodyne signals corresponding to the modified electrical signals
20   to generate at least one modified superheterodyne signal containing phase corresponding to the dispersion of the refractive index of the gas and to the dispersion of the optical path length of the measurement leg due to the dispersion of the refractive index of the gas. Means are
25   also included for resolving phase ambiguities of the heterodyne signals, modified heterodyne signals, and the modified superheterodyne signals generated in certain of the embodiments. Depending on the details of the optical paths experienced by the light beam portions as they
30   travel through the interferometer means of the various embodiments, additional or different electronics are provided.

18

While the inventive method disclosed may be carried out using the preferred apparatus described, it will be evident that it may also be practiced using other well-known apparatus. In addition, it is shown that apparatus 5   may be employed which uses homodyne signals.

BRIEF DESCRIPTION OF THE DRAWINGS

10   The structure and operation of the invention, together with other objects and advantages thereof, may best be understood by reading the detailed description in conjunction with the drawings wherein the invention's parts have an assigned reference numeral that is used to 15   identify them in all of the drawings in which they appear and wherein:

FIGS. **1a-1b** taken together illustrate, in diagrammatic form, the presently first preferred embodiment of the present invention with FIG. **1a** showing 20   optical paths between indicated elements source **1**, modulator **3**, source **2**, modulator **4**, interferometer **260**, detectors **85** and **86**, and translator **267** and the paths of electrical signals between indicated elements driver **5**, modulator **3**, driver **6**, modulator **4**, detectors **85** and **86**, 25   electronic processor **109**, and computer **110**;

FIG. **1b** is a drawing showing a block diagram of the processing electronics **109**;

FIG. **1c** is a drawing showing a block diagram of the processing electronics **109A** for the first variant of the 30   first embodiment;

19

FIG. **1d** is a drawing showing a block diagram of the processing electronics **109B** for the third variant of the first embodiment;

FIGS. **2a-2f** taken together illustrate, in
5   diagrammatic form, the presently second preferred embodiment of the present invention with FIG. **2a** showing optical paths between indicated elements source **1**, modulator **3**, source **2**, modulator **4**, differential plane mirror interferometers **69** and **70**, beam splitter **65**,
10   external mirror system **90**, detectors **185** and **186**, and translator **67** and the paths of electrical signals between indicated elements driver **5**, modulator **3**, driver **6**, modulator **4**, detectors **185** and **186**, electronic processor **209**, and computer **110**;
15   FIG. **2b** illustrates differential plane mirror interferometer **69**;

FIG. **2c** illustrates differential plane mirror interferometer **70**;

FIG. **2d** illustrates external mirror system **90**,
20   furnishing the external mirrors for differential plane mirror interferometer **69**, and stage translator **67**;

FIG. **2e** illustrates external mirror system **90**, furnishing the external mirrors for differential plane mirror interferometer **70**, and stage translator **67**;
25   FIG. **2f** is a drawing showing a block diagram of the processing electronics **209**;

FIGS. **3a-3b** taken together illustrate, in diagrammatic form, the presently preferred third embodiment of the present invention with FIG. **3a** showing
30   optical paths and electronic paths of apparatus for determination of refractive index of a gas and/or the

20

optical path length effects of the gas comprised in part
of the same apparatus as for the first preferred
embodiment and optical paths and electronic paths of
apparatus for determination of χ and the ratio K/χ, a
5   number of elements of the apparatus for determination of
χ and the ratio K/χ performing analogous operations as
apparatus of the first preferred embodiment apart from the
suffix "b" when referring to apparatus for determination
of χ and the ratio K/χ;

10   FIG. **3b** is a drawing showing a block diagram of the
processing electronics **109b**;

         FIGS. **4a-4c** taken together illustrate, in
diagrammatic form, the presently preferred fourth
embodiment of the present invention with FIG. **4a** showing
15   optical paths and electronic paths of apparatus for
determination of refractive index of a gas and/or the
optical path length effects of the gas comprised in part
of the same apparatus as for the second preferred
embodiment and optical paths and electronic paths of
20   apparatus for determination of the χ and ratio K/χ, a
number of elements of the apparatus for determination of
χ and the ratio K/χ performing analogous operations as
apparatus of the second preferred embodiment apart from
the suffix "b" when referring to apparatus for
25   determination of χ and the ratio K/χ;

         FIG. **4b** illustrates the external mirror system **90b**
furnishing the external mirrors for differential plane
mirror interferometer **69b**;

         FIG. **4c** illustrates the external mirror system **90b**
30   furnishing the external mirrors for differential plane
mirror interferometer **70b**;

Fig. **5** is a high-level flowchart depicting various steps carried out in practicing a method in accordance with the invention;

FIG. **6a-6c** relate to lithography and its application

5   to manufacturing integrated circuits wherein FIG. **6a** is a schematic drawing of a lithography exposure system employing the interferometry system.

FIGS. **6b** and **6c** are flow charts describing steps in manufacturing integrated circuits; and

10   FIG. **7** is a schematic of a beam writing system employing the interferometry system.

DETAILED DESCRIPTION OF THE

15   INVENTION

The present invention relates to apparatus and methods by which the refractivity of a gas in at least one measurement path and/or the change in the optical path

20   length of the measurement path due to the gas may be quickly measured and used in subsequent downstream or contemporaneous applications wherein either or both the refractive index of the gas and the physical length of the measurement path may be changing. An example of a

25   contemporaneous application is in an interferometric distance measuring instrument to enhance accuracy by compensating for the effects of the refractive index of the gas in the measurement path, especially changes in the optical path length that take place during the measuring

30   period because of changing environmental conditions or air turbulence induced in the measurement path by rapid stage slew rates.

A number of different embodiments of the apparatus of
the invention are shown and described. While they differ
in some details, the disclosed embodiments otherwise share
many common elements and naturally fall into two
5   categories depending on the degree of control demanded of
their light sources. As will be seen, the disclosed
embodiments within each category also differ in the
details of how their interferometric optical paths are
implemented and/or how certain information signals are
10 handled electronically.

The first group of embodiments to be described
comprise two embodiments and variants thereof. This group
is intended for applications where the stability of the
adopted light sources is sufficient and the ratio of the
15 wavelengths of the light beams generated by the adopted
light sources is matched to a sequence of known ratio
values with respective relative precisions sufficient to
meet the required precision imposed on the output data by
the final end use application.

20   The second group of embodiments also comprise two
embodiments and variants thereof and these are
particularly suitable for use where it is necessary to
monitor the stability of the light sources and measure the
ratios of the wavelengths of the light beams generated by
25 the adopted light sources to meet performance requirements
on accuracy. For both groups, apparatus is disclosed for
dealing with phase ambiguities and phase and group delays
that may arise in analyzing homodyne, heterodyne, and/or
superheterodyne signals and methods are disclosed for
30 implementing the steps of the invention.

FIGS. **1a** and **1b** depict in schematic form one
preferred embodiment of the present invention for
measuring and monitoring the refractivity of a gas in a

23

measurement path and/or the change in the optical path
length of the measurement path due to the gas wherein
either or both the refractive index of the gas and the
physical length of the measurement path may be changing

5   and where the stability of the adopted light sources is
sufficient and the ratio of the wavelengths of the light
beams generated by the adopted light sources is matched to
a known ratio value with a relative precision sufficient
to meet the required precision imposed on the output data

10   by the final end use application. While the apparatus has
application for a wide range of radiation sources, the
following description is taken by way of example with
respect to an optical measuring system.

        Referring to FIG. **1a** and in accordance with the

15   preferred apparatus and method of the first preferred
embodiment of the present invention, a light beam **7**
emitted from source **1** passes through a modulator **3**
becoming light beam **9**. Modulator **3** is excited by a driver
5. Source **1** is preferably a laser or like source of

20   coherent radiation, preferably polarized, and having a
wavelength λ_1. Modulator **3** may for example be an acousto-
optical device or a combination of acousto-optical devices
with additional optics for selectively modulating
polarization components of beam **7**. Modulator **3** preferably

25   shifts the oscillation frequency of one linearly polarized
component of beam **7** an amount f_1 with respect to an
orthogonally linearly polarized component, the directions
of polarizations of the components denoted herein as x
and y. In the following description of the first

30   preferred embodiment, it will be assumed that the x
polarization component of beam **9** has an oscillation
frequency shifted an amount f_1 with respect to the y

polarization component of beam **9** without departing from
the spirit or scope of the present invention.   The
oscillation frequency f_1 is determined by the driver **5**.

5   In a next step, a light beam **8** emitted from a source
2 passes through a modulator **4** becoming light beam **10**.
Modulator **4** is excited by a driver **6**, similar to modulator
3 and driver **5**, respectively.   Source **2**, similar to source
1, is preferably a laser or like source of polarized,
coherent radiation, but preferably at a different

10   wavelength, λ_2, wherein the ratio of the wavelengths
(λ_1/λ_2) has a known approximate ratio value l_1/l_2, i.e.

$$(\lambda_1/\lambda_2) \cong (l_1/l_2) \quad , \tag{1}$$

15   where l_1 and l_2 may assume integer and non-integer values,
and the ratio of the wavelengths (λ_1/λ_2) is the same as the
ratio value l_1/l_2 to a relative precision of an order of
magnitude or more less than the dispersion of the
refractive index of the gas, $(n_2 - n_1)$, times the relative

20   precision ε desired for the measurement of the
refractivity of the gas or of the change in the optical
path length of the measurement leg due to the gas.   The x
polarized component of beam **10** has an oscillation
frequency shifted an amount f_2 with respect to the y

25   polarized component of beam **10**.   The oscillation frequency
f_2 is determined by the driver **6**.   In addition, the
directions of the frequency shifts of the x components of
beams **9** and **10** are the same.

        It will be appreciated by those skilled in the art

30   that beams **7** and **8** may be provided alternatively by a

single laser source emitting more than one wavelength, by a single laser source combined with optical frequency doubling means to achieve frequency doubling, tripling, quadrupling, *etc.*, two laser sources of differing

5   wavelengths combined with sum-frequency generation or difference-frequency generation, or any equivalent source configuration capable of generating light beams of two or more wavelengths.

A laser source, for example, can be a gas laser, *e.g.*

10 a HeNe, stabilized in any of a variety of conventional techniques known to those skilled in the art, see for example, T. Baer *et al.*, "Frequency Stabilization of a 0.633 μm He-Ne-longitudinal Zeeman Laser," *Applied Optics*, **19**, 3173-3177 (1980); Burgwald *et al.*, U.S. Pat.

15 No. 3,889,207, issued June 10, 1975; and Sandstrom *et al.*, U.S. Pat. No. 3,662,279, issued May 9, 1972. Alternatively, the laser can be a diode laser frequency stabilized in one of a variety of conventional techniques known to those skilled in the art, see for example, T.

20 Okoshi and K. Kikuchi, "Frequency Stabilization of Semiconductor Lasers for Heterodyne-type Optical Communication Systems," *Electronic Letters*, **16**, 179-181 (1980) and S. Yamaqguchi and M. Suzuki, "Simultaneous Stabilization of the Frequency and Power of an AlGaAs

25 Semiconductor Laser by Use of the Optogalvanic Effect of Krypton," *IEEE J. Quantum Electronics*, **QE-19**, 1514-1519 (1983).

It will also be appreciated by those skilled in the art that the two optical frequencies of beam **9** and of beam

30 **10** may be produced by any of a variety of frequency modulation apparatus and/or lasers: (1) use of a Zeeman split laser, see for example, Bagley *et al.*, U.S. Patent

No. 3,458,259, issued Jul. 29, 1969; G. Bouwhuis,

"Interferometrie Mit Gaslasers," Ned. T. Natuurk, **34**, 225-

232 (Aug. 1968); Bagley *et al.*, U.S. Patent No. 3,656,853,

issued Apr. 18, 1972; and H. Matsumoto, "Recent

5   interferometric measurements using stabilized lasers,"

Precision Engineering, **6**(2), 87-94 (1984); (2) use of a

pair of acousto-optical Bragg cells, see for example, Y.

Ohtsuka and K. Itoh, "Two-frequency Laser Interferometer

for Small Displacement Measurements in a Low Frequency

10   Range," *Applied Optics*, **18**(2), 219-224 (1979); N. Massie

et al., "Measuring Laser Flow Fields With a 64-Channel

Heterodyne Interferometer," *Applied Optics*, **22**(14), 2141-

2151 (1983); Y. Ohtsuka and M. Tsubokawa, "Dynamic Two-

frequency Interferometry for Small Displacement

15   Measurements," *Optics and Laser Technology*, **16**, 25-29

(1984); H. Matsumoto, *ibid.*; P. Dirksen, *et al.*, U.S.

Patent No. 5,485,272, issued Jan. 16, 1996; N. A. Riza and

M. M. K. Howlader, "Acousto-optic system for the

generation and control of tunable low-frequency signals,"

20   *Opt. Eng.*, **35**(4), 920-925 (1996); (3) use of a single

acousto-optic Bragg cell, see for example, G. E.

Sommargren, commonly owned U.S. Patent No. 4,684,828,

issued Aug. 4, 1987; G. E. Sommargren, commonly owned U.S.

Patent No. 4,687,958, issued Aug. 18, 1987; P. Dirksen, *et*

25   *al.*, *ibid.*; (4) use of two longitudinal modes of a

randomly polarized HeNe laser, see for example, J. B.

Ferguson and R. H. Morris, "Single Mode Collapse in 6328 Å

HeNe Lasers," *Applied Optics*, **17**(18), 2924-2929 (1978); or

(5) use of birefringent elements or the like internal to

30   the laser, see for example, V. Evtuhov and A. E. Siegman,

"A 'Twisted-Mode' Technique for Obtaining Axially Uniform

Energy Density in a Laser Cavity," *Applied Optics*, **4**(1), 142-143 (1965).

The specific device used for the sources of beams **7** and **8** will determine the diameter and divergence of beams
5   **7** and **8**, respectively. For some sources, *e.g.*, a diode laser, it will likely be necessary to use conventional beam shaping optics, *e.g.*, a conventional microscope objective, to provide beams **7** and **8** with a suitable diameter and divergence for the elements that follow. .
10 When the source is a HeNe laser, for example, beam shaping optics may not be required.

It will be further appreciated by those skilled in the art that both the x and y polarization components of beam **9** and/or of beam **10** may be frequency shifted without
15 departing from the scope and spirit of the invention, f_1 remaining the difference in frequencies of the x and y polarization components of beam **9** and f_2 remaining the difference in frequencies of the x and y polarization components of beam **10**. Improved isolation of an
20 interferometer and a laser source is generally possible by frequency shifting both x and y polarization components of a beam, the degree of improved isolation depending on the means used for generating the frequency shifts.

In a next step, beam **9** is reflected by mirror **253A**
25 and then a portion of beam **9** is subsequently reflected by beamsplitter **253B**, preferably a non-polarizing type, to become a component of beam **213**, the λ_1 component. A portion of beam **10** is transmitted by beamsplitter **253B** to become a second component of beam **213**, the λ_2 component,
30 wherein the λ_2 component is preferably parallel and coextensive with the λ_1 component. In a further step,

beam **213** propagates to an interferometer **260**, comprised of
optical means for a introducing a phase shift φ_1 between
the polarization components x and y of the λ_1 component of
beam **213** and a phase shift φ_2 between the polarization

5 components x and y of the λ_2 component of beam **213**. The
magnitude of phase shifts φ_1 and φ_2 are related to
round-trip physical length L of measurement path **298**
according to the formulae

10 $$\varphi_j = Lpk_j n_j + \zeta_j \quad , \quad j = 1 \text{ and } 2, \tag{2}$$

where p is the number of passes through the respective
reference and measurement legs for a multiple pass
interferometer, and n_j are the refractive indices of gas

15 in measurement path **298** corresponding to wavenumber
$k_j = (2\pi)/\lambda_j$. The phase offsets ζ_j comprise all
contributions to the phase shifts φ_j that are not related
to the measurement path **298** or reference paths.

　　　As shown in FIG. **1a**, interferometer **260** is comprised

20 of a reference retroreflector **295**, object retroreflector
296, quarter-wave phase retardation plates **221** and **222**,
and a polarizing beam splitter **223**. This configuration is
known in the art as a polarized Michelson interferometer,
and is shown as a simple illustration with $p = 1$.

25 　　　Eqs. (2) are valid for the case where the paths for
one wavelength and the paths for the second wavelength are
substantially coextensive, a case chosen to illustrate in
the simplest manner the function of the invention in the
first embodiment. To those skilled in the art, the

30 generalization to the case where the respective paths for

29

the two different wavelengths are not substantially coextensive is a straight forward procedure.

Cyclic errors that produce nonlinearities in distance measuring interferometry (*cf.* the cited articles by

5   Bobroff) have been omitted in Eqs. (2). Techniques known to those skilled in the art can be used to either reduce the cyclic errors to negligible levels or compensate for the presence of cyclic errors, techniques such as using separated beams in the interferometer and/or separated

10   beams in the delivery system for light beams from each light beam source to the interferometer [M. Tanaka, T. Yamagami, and K. Nakayama, "Linear Interpolation of Periodic Error in a Heterodyne Laser Interferometer at Subnanometer Levels," *IEEE Trans. Instrum. and Meas.*,

15   **38**(2), 552-554, 1989] and light beam sources with reduced polarization and/or frequency mixing.

After passing through interferometer **260**, beam **213** becomes a phase-shifted beam **215**, which passes through a polarizer **244** preferably orientated so as to mix

20   polarization components x and y of beam **215**. A conventional dichroic beam splitter **280** preferably separates those portions of beam **215** corresponding to wavelengths λ_1 and λ_2 into beams **217** and **218**, respectively.

25   In a next step as shown in FIG. **1a**, phase-shifted beams **217** and **218** impinge upon photodetectors **85** and **86**, respectively, resulting in two electrical interference signals, heterodyne signals s_1 and s_2, respectively, preferably by photoelectric detection. The signal s_1

30   corresponds to wavelength λ_1 and signal s_2 corresponds to the wavelength λ_2. The signals s_j have the form

30

$$s_j = A_j \cos\left[\alpha_j(t)\right] \quad , \quad j = 1 \text{ and } 2 \quad , \tag{3}$$

where the time-dependent arguments $\alpha_j(t)$ are given by

5

$$\alpha_j(t) = 2\pi f_j t + \varphi_j \quad , \quad j = 1 \text{ and } 2 \quad . \tag{4}$$

Heterodyne signals s_1 and s_2 are transmitted to electronic
processor 109 for analysis as electronic signals 103 and
10   104, respectively, in either digital or analog format,
preferably in digital format.

A preferred method for electronically processing the
heterodyne signals s_1 and s_2 is presented herewithin for
the case when l_1 and/or l_2 are not low order integers. For
15   the case when l_1 and l_2 are both low order integers and the
ratio of the wavelengths matched to the ratio (l_1/l_2) with a
relative precision sufficient to meet the required
precision imposed on the output data by the end use
application, the preferred procedure for electronically
20   processing the heterodyne signals s_1 and s_2 is the same as
the one subsequently set down for the second variant of
the first preferred embodiment of the present invention.

Referring now to FIG. 1b, electronic processor 109
further comprises electronic processors 1094A and 1094B to
25   determine the phases φ_1 and φ_2, respectively, by either
digital or analog signal processes, preferably digital
processes, using time-based phase detection such as a
digital Hilbert transform phase detector [see section
4.1.1 of "Phase-locked loops: theory, design, and

31

applications" 2nd ed. McGraw-Hill (New York) 1993, by R.
E. Best] or the like and the phase of drivers **5** and **6**.

    The phases of drivers **5** and **6** are transmitted by
electrical signals, reference signals **101** and **102**,

5   respectively, in either digital or analog format,
preferably in digital format, to electronic processor **109**.
Reference signals, alternatives to reference signals **101**
and **102**, may also be generated by an optical pick off
means and detectors (not shown in figures) by splitting

10   off portions of beams **9** and **10** with beam splitters,
preferably non-polarizing beam splitters, mixing the
portion of the beam **9** and the portion of the beam **10** that
are split off, and detecting the mixed portions to produce
alternative heterodyne reference signals.

15   Referring again to FIG. 1b, phase φ_1 and phase φ_2
are next multiplied by l_1/p and l_2/p, respectively, in
electronic processors **1095A** and **1095B**, respectively,
preferably by digital processing, resulting in phases
$(l_1/p)\varphi_1$ and $(l_2/p)\varphi_2$, respectively. The phases $(l_1/p)\varphi_1$ and

20   $(l_2/p)\varphi_2$ are next added together in electronic processor
1096A and subtracted one from the other in electronic
processor **1097A**, preferably by digital processes, to
create the phases ϑ and Φ, respectively. Formally,

25

$$\vartheta = \left(\frac{l_1}{p}\varphi_1 + \frac{l_2}{p}\varphi_2\right) \quad , \tag{5}$$

$$\Phi = \left(\frac{l_1}{p}\varphi_1 - \frac{l_2}{p}\varphi_2\right) \quad . \tag{6}$$

The phases φ_1, ϑ, and Φ are transmitted to computer **110** as signal **105**, in either digital or analog format, preferably in digital format.

For a measuring path comprised of a vacuum, phase Φ
5   should substantially be a constant independent of Doppler shifts due to a motion of retroreflector **296**. This may not be the case in practice due to differences in the group delay experienced by the electrical signals s_1 and s_2. Group delay, often called envelope delay, describes
10   the delay of a packet of frequencies, and the group delay at a particular frequency is defined as the negative of the slope of the phase curve at the particular frequency [see H. J. Blinchikoff and A. I. Zverev, *Filtering in the Time and Frequency Domains*, Section 2.6, 1976 (Wiley, New
15   York)]. If phase Φ is not a constant for a measuring path comprised of a vacuum, techniques known to those skilled in the art can be used to compensate for departures of phase Φ from a constant (*cf.* Blinchikoff and Zveriv, *ibid*.). It is important to note that the
20   group delay effects in Φ can not only be detected but can also be determined by measuring Φ as a function of different translational velocities of retroreflector **296** produced by translator **267** for a measuring path comprising a vacuum. It is also important to note that the group
25   delay effects in Φ can be significantly reduced by performing analog-to-digital conversion of signals s_1 and s_2 as close as practical to the photoelectric detectors in detectors **85** and **86**, respectively, followed by digital signal processing as opposed to transmitting the signals
30   s_1 and s_2 as analog signals for subsequent analog signal processing and/or analog-to-digital conversion downstream.

The compensation for a particular group delay can generally be introduced before or after, or in part before and in part after, the processing elements producing the particular group delay.

5   The refractivity of the gas, $(n_1 - 1)$, can be calculated using the formula

$$n_1 - 1 = \frac{\Gamma}{\chi L \left[1 - (K/\chi)^2\right]} \left\{\left[\vartheta(K/\chi) - \Phi\right] - Q\right\} \quad , \tag{7}$$

10   where

$$\chi = (l_1 k_1 + l_2 k_2)/2 \quad , \tag{8}$$

$$K = (l_1 k_1 - l_2 k_2)/2 \tag{9}$$

15

and

$$\Gamma = \frac{n_1 - 1}{n_2 - n_1} \quad , \tag{10}$$

20   the quantity Γ being the reciprocal dispersive power of the gas which is substantially independent of environmental conditions and turbulence in the gas. The offset term Q is defined as

25   $$Q = \xi(K/\chi) - Z \tag{11}$$

where

34

$$\xi = \left(\frac{l_1}{p} \zeta_1 + \frac{l_2}{p} \zeta_2 \right) \quad , \tag{12}$$

$$Z = \left(\frac{l_1}{p} \zeta_1 - \frac{l_2}{p} \zeta_2 \right) \quad . \tag{13}$$

5   Values of Γ may be computed from knowledge of the
gas composition and from knowledge of the wavelength
dependent refractivities of the gas constituents. For the
example of $\lambda_1 = 0.63 \ \mu m$, $\lambda_2 = 0.32 \ \mu m$, and a standard
atmosphere, $\Gamma \cong 24$.

10   In addition, Eq. (7) is valid for the case where the
combined paths for optical beams at one wavelength are
substantially coextensive with the combined paths for
optical beams at a second wavelength, a preferred
configuration that also serves to illustrate in the

15   simplest manner the function of the invention. To those
skilled in the art, the generalization to the case where
combined paths for optical beams at one wavelength are not
substantially coextensive with the combined paths for
optical beams at a second wavelength is a straight forward

20   procedure.

       For those applications related to distance measuring
interferometry, the heterodyne phase φ_1 and phases ϑ and
Φ may be used to determine a physical distance L,
independent of the effects of the refractive index of the

25   gas in the measuring path of a distance measuring
interferometer, using the formula

35

$$L = \frac{1}{(\chi + K)} \left\{ \frac{l_1}{p}(\varphi_1 - \zeta_1) - \frac{\Gamma}{[1 - (K/\chi)]}[(K/\chi)\vartheta - \Phi - Q] \right\} \quad . \qquad (14)$$

The ratio of the wavelengths can be expressed in terms of (K/χ) from Eqs. (8) and (9) with the result

$$\frac{\lambda_1}{\lambda_2} = \left(\frac{l_1}{l_2} \right) \left[\frac{1 - (K/\chi)}{1 + (K/\chi)} \right] \quad . \qquad (15)$$

When operating under the condition

$$|K/\chi| \ll \frac{(n_2 - n_1)}{(n_2 + n_1)} \quad , \qquad (16)$$

the ratio of the phases Φ and ϑ has the approximate value

$$(\Phi/\vartheta) \cong -\frac{(n_2 - n_1)}{(n_2 + n_1)} \quad . \qquad (17)$$

Therefore, for the case of the first preferred embodiment where the ratio of the wavelengths (λ_1/λ_2) has a known approximate ratio value l_1/l_2, cf. Eq. (1), where l_1 and l_2 may assume integer and non-integer values, and the ratio of the wavelengths (λ_1/λ_2) is the same as the ratio value l_1/l_2 to a relative precision of an order of magnitude or more less than the dispersion of the refractive index of the gas, $(n_2 - n_1)$, times the relative precision ε desired for the measurement of the refractivity of the gas or of

36

the change in the optical path length of the measurement leg due to the gas, expressed formally by the inequality

$$\left|\frac{\lambda_1}{\lambda_2} - \frac{l_1}{l_2}\right| \ll \left(\frac{l_1}{l_2}\right)(n_2 - n_1)\varepsilon \qquad , \tag{18}$$

5

Eqs. (7) and (14) reduce to more simple forms of

$$n_1 - 1 = -\frac{\Gamma}{\chi L}(\Phi + Q) \qquad , \tag{19}$$

10
$$L = \frac{1}{\chi}\left[\frac{l_1}{P}(\varphi_1 - \zeta_1) + \Gamma(\Phi + Q)\right] \qquad , \tag{20}$$

respectively. It will also be obvious to someone skilled in the art to perform similar calculations for L with respect to n_2,

15
$$(n_2 - 1) = (n_1 - 1)(1 + 1/\Gamma) \qquad , \tag{21}$$

in place of or in addition to n_1.

In a next step, electronic processing means **109**
20 transmits to the computer **110** φ_1 and Φ as electronic signal **105** in either digital or analog format, preferably a digital format, for the computation of $(n_1 - 1)$ and/or L. The resolution of phase redundancy in $(1/l_1)\Phi$ is required in the computation of either $(n_1 - 1)$ or changes in L due to
25 the gas using either Eqs. (19) or (20), respectively. In addition, the resolution of phase redundancy in φ_1 is required in the computation of L using Eq. , and the

37

resolution of the phase redundancy in φ_1 is required in the computation of changes L using Eq. (20) if χ is variable in time.

The equivalent wavelength comprising $(1/l_1)\Phi$ is
5   significantly larger than either of the wavelengths λ_1 and λ_2 and as a consequence, produces a significant simplification in a procedure implemented for resolution of phase redundancy in $(1/l_1)\Phi$. The equivalent wavelength $\lambda_{(1/l_1)\Phi}$ for $(1/l_1)\Phi$ is

10

$$\lambda_{(1/l_1)\Phi} = \frac{\lambda_1}{(n_2 - n_1)} \quad . \tag{22}$$

For the example of $\lambda_1 = 0.63 \ \mu m$, $\lambda_2 = 0.32 \ \mu m$, and $(n_2 - n_1) \cong 1 \times 10^{-5}$ for a standard atmosphere, the equivalent
15   wavelength given by Eq. (22) is

$$\lambda_{(1/l_1)\Phi} \cong 63 \ mm \quad . \tag{23}$$

Any one of several procedures may be easily employed
20   to resolve the phase redundancy in $(1/l_1)\Phi$, given the equivalent wavelength as expressed by Eq. (22). For those applications where changes in the measurement path can be measured interferometrically, a feature for example of an application based on a distance measuring interferometer
25   employed for measuring changes in the measurement path, the movable retroreflector 296 of interferometer 260 can be scanned by translator 267 in a controlled manner over a given length and the concomitant change in $(1/l_1)\Phi$

recorded. From the recorded change in $(1/l_1)\Phi$ and the
length scanned, as recorded by the change in φ_1, the
equivalent wavelength $\lambda_{(1/l_1)\Phi}$ can be calculated. With the
computed value for the equivalent wavelength $\lambda_{(1/l_1)\Phi}$, the

5   phase redundancy in $(1/l_1)\Phi$ can be easily resolved in view
of the relatively large value for the equivalent
wavelength $\lambda_{(1/l_1)\Phi}$.

For those applications where the determination of the
refractivity and/or or the change in the optical path
10   length due to the gas in a measurement leg is made and
retroreflector 296 does not have a scanning capability
such as considered in the preceding paragraph, other
procedures are available for the resolution of the phase
redundancy of $(1/l_1)\Phi$. One procedure which may be employed
15   to resolve the phase redundancy in $(1/l_1)\Phi$ is based on the
use of a retroreflector or series of retroreflectors
inserted at a series of positions in measurement path 298,
the retroreflector at each position of the series of
positions performing the same function as retroreflector
20   296, wherein the round-trip physical length L for the
measurement leg for each position of the series of
positions of the inserted retroreflectors form a geometric
progression. The smallest or first round-trip physical
length in the series of positions will be approximately
25   $\lambda_1/\left[4(n_2 - n_1)\right]$ divided by the relative precision that the
initial value of $(1/l_1)\Phi$ is known. The round-trip physical
length of the second position of the series of positions
will be approximately the round-trip physical length of
the first position of the series of positions divided by

39

the relative precision that Φ is measured using the first position of the series of positions. This is a geometric progression procedure, the resulting sequence of round-trip physical lengths forming a geometric progression,

5 which is continued until the round-trip physical length of the retroreflector **296** used to measure the refractivity or the change in optical path length due to the refractivity of the gas would be exceeded if the number of positions in the series of positions were incremented by one.

10 A third procedure is based upon the use of a source (not shown in FIGS. **1a** and **1b**) of a series of known wavelengths and measuring Φ for these wavelengths. The number of known wavelengths required for the resolution of the phase redundancy is generally comprised of a small set

15 because of the relatively large value for $\lambda_{(1/l_1)\Phi}$ as given by Eq. (22).

Another procedure to resolve the phase redundancy in $(1/l_1)\Phi$ would be to observe the changes in $(1/l_1)\Phi$ as the measuring path **98** is changed from being filled with a gas

20 to an evacuated state (the vacuum chamber and pump and requisite gas handling system are not shown in FIGS. **1a** and **1b**) to resolve the phase redundancy in $(1/l_1)\Phi$. The problems normally encountered in measuring absolute values for refractivity and changes in the optical path length

25 due to the refractivity of the gas based in part on changing the gas pressure from a non-zero value to a vacuum are not present in the first preferred embodiment because of the relative large equivalent wavelength of $(1/l_1)\Phi$ as expressed by Eq. (22).

30 The resolution of the phase redundancy in φ_1, if required, presents a problem similar to the one as

subsequently described with respect to the required resolution of phase redundancy in ϑ in the fourth embodiment and variants thereof of the present invention. As a consequence, the procedure described for the

5   resolution of phase redundancy in ϑ with respect to the fourth embodiment and variants thereof can be adapted for use in the resolution of the phase redundancy in φ_1.

The offset terms involving ζ_1 or/and Q that are present in Eqs. (19) and (20) and defined in Eqs. (2) and

10   (11) are terms that require some combination of determination and/or monitoring depending on whether χ is variable in time, whether the refractivity or/and the length L are to be determined, respectively, or whether changes in refractivity or/and the length L are to be

15   determined, respectively. The determination and/or monitoring of ζ_1 or/and Q as required presents a problem similar to the one as subsequently described with respect to the determination and/or monitoring of ζ_3 and/or Q in the second and fourth embodiments and variants thereof of

20   the present invention. As a consequence, the procedures described for the determination and/or monitoring of ζ_3 and/or Q with respect to the second and fourth embodiments and variants thereof can be adapted for use in the first embodiment for the determination and/or

25   monitoring of ζ_1 and/or Q as required.

A first variant of the first preferred embodiment is disclosed wherein the description of the apparatus of the first variant of the first embodiment is the same as that given for the apparatus of the first embodiment except

30   with regard to the detection of beams **217** and **218** of the first embodiment shown in FIG. **1a**. In the first variant

41

of the first embodiment, a first portion of beam **217** is detected by a detector (not shown in the figures) creating a signal proportional to s_1, as_1 where a is a constant, and beam **218** and a second portion of beam **217** are detected

5   by a second single detector (not shown in the figures) creating signal $S_{b1+2} = bs_1 + s_2$ where b is a constant. Heterodyne signals as_1 and S_{b1+2} are transmitted as electronic signals **1103** and **1104**, respectively, in either digital or analog format, preferably in digital format, to

10   electronic processor **109A** shown in diagrammatic form in FIG. **1c** for analysis.

Referring now to FIG. **1c**, electronic processor **109A** preferably comprises alphameric numbered elements wherein the numeric component of the alphameric numbers indicate

15   the function of an element, the same numeric component/function association as described for the electronic processing elements of the first embodiment depicted in FIG. **1b**. The description of the steps performed by electronic processor **109A** in processing

20   heterodyne signals bs_1 and s_2 comprising S_{b1+2} for phases ϑ and Φ is the same as corresponding portions, according to the numeric component of the alphameric numbers of elements, of the description of steps performed by electronic processor **109** in processing heterodyne signals

25   s_1 and s_2 of the first embodiment. The description of the steps in processing heterodyne signal as_1 by electronic processor **109A** for phase φ_1 is the same as corresponding portions, according to the numeric component of the alphameric numbers of elements, of the description of

30   steps in the processing of the heterodyne signal s_1 of the first embodiment by electronic processor **109**.

The phases φ_1, ϑ, and Φ created by electronic processor **109A** formally have the same properties as φ_1, ϑ, and Φ, respectively, created by electronic processor **109** of the second embodiment.

5   The feature of the first variant of the first embodiment which can be a significant feature is the detection the optical beams creating heterodyne signals bs_1 and s_2 by a single detector. It will be apparent to those skilled in the art that the single detector feature

10   of the first variant of the first embodiment can be important in reducing or eliminating the effects of differences in certain group delays possible in the first embodiment. The remaining description of the first variant of the first embodiment is the same as

15   corresponding portions of the description given for the first embodiment.

A second variant of the first preferred embodiment is disclosed wherein the description of the apparatus of the second variant of the first embodiment is the same as that

20   given for the apparatus of the first embodiment except with regard to the frequencies f_1 and f_2 of drivers **5** and **6**, respectively, shown in FIG. **1a**. In the second variant of the first embodiment, the frequencies of the two drivers **5** and **6** are the same, *i.e.* $f_1 = f_2$. This feature

25   of the second variant of the first embodiment eliminates the effects of differences in group delays in the first embodiment resulting from $f_1 \neq f_2$. The remaining description of the second variant of the first embodiment is the same as the corresponding portions of

30   the description given for the first preferred embodiment.

Reference is now made to FIGS. **1a** and **1d** which taken together depict in diagrammatic form a third variant of

43

the first preferred embodiment of the present invention
for measuring and monitoring the refractivity of a gas in
a measurement path and/or the change in the optical path
length of the measurement path due to the gas wherein

5   either or both the refractive index of the gas and the
physical length of the measurement path may be changing
and where the stability of the adopted light sources is
sufficient and the wavelengths of the light beams
generated by the adopted light sources are harmonically

10   related to a relative precision sufficient to meet the
required precision imposed on the output data by the final
end use application. The condition wherein the
wavelengths are approximately harmonically related
corresponds to the special case of the first embodiment in

15   which the ratio (l_1/l_2) is expressible as the ratio of low

order non-zero integers (p_1/p_2), i.e.

$$l_1 = p_1 \quad , \quad l_2 = p_2 \quad ,$$
$$\left(\frac{l_1}{l_2}\right) = \left(\frac{p_1}{p_2}\right) \quad , \quad p_1, p_2 = 1, 2, \ldots \quad , \quad p_1 \neq p_2 \quad . \tag{24}$$

20   The description of the sources of light beams **9** and
10 and of light beams **9** and **10** for the second variant of
the first embodiment is the same as that for description
of the sources of light beams **9** and **10** and of light beams
9 and **10** given for the first embodiment with the

25   additional requirement that the wavelengths be
harmonically related to a relative precision sufficient to
meet the required precision imposed on the output data by
the final end use application. The description of the
apparatus for the second variant of the first embodiment

44

depicted in FIG. **1a** is the same as corresponding portions of the description given for the first embodiment.

Referring now to FIG. **1d**, electronic processing means **109B** preferably comprises means **1092A** and **1092B** for electronically multiplying time-dependent arguments $\alpha_1(t)$ and $\alpha_2(t)$, respectively, of heterodyne signals s_1 and s_2, respectively, by coefficients p_1 and p_2, respectively, so as to create two modified heterodyne signals $\tilde{s}_1$ and $\tilde{s}_2$ having the form

$$\tilde{s}_j = \tilde{A}_j \cos\left[p_j \alpha_j(t)\right] \quad , \quad j = 1 \text{ and } 2 \quad . \tag{25}$$

The multiplication may be achieved by any one of the conventional frequency multiplying techniques commonly known in the art, such as signal squaring followed by electronic filtering.

Referring again to FIG. **1d**, electronic processing means **109B** preferably comprises means **1095E** for electronically multiplying together, either as an analog or digital process, preferably a digital process, modified heterodyne signals $\tilde{s}_1$ and $\tilde{s}_2$ to create a superheterodyne signal $S_{\tilde{1}\times\tilde{2}}$ having the mathematical form

$$S_{\tilde{1}\times\tilde{2}} = \tilde{s}_1 \tilde{s}_2 \quad . \tag{26}$$

The superheterodyne signal $S_{\tilde{1}\times\tilde{2}}$ is comprised of two sidebands with a suppressed carrier and may be rewritten as

$$S_{\tilde{1}\times\tilde{2}} = S_{\tilde{1}\times\tilde{2}}^{+} + S_{\tilde{1}\times\tilde{2}}^{-} \qquad\qquad (27)$$

where

$$S_{\tilde{1}\times\tilde{2}}^{+} = \frac{1}{2}\tilde{A}_1\tilde{A}_2\cos\left(2\pi\tilde{\nu}t + \tilde{\vartheta}\right) \quad , \qquad\qquad (28)$$

$$S_{\tilde{1}\times\tilde{2}}^{-} = \frac{1}{2}\tilde{A}_1\tilde{A}_2\cos\left(2\pi\tilde{F}t + \tilde{\Phi}\right) \quad , \qquad\qquad (29)$$

$$\tilde{\nu} = \left(p_1 f_1 + p_2 f_2\right) \quad , \qquad\qquad (30)$$

$$\tilde{\vartheta} = \left(p_1\varphi_1 + p_2\varphi_2\right) \quad , \qquad\qquad (31)$$

$$\tilde{F} = \left(p_1 f_1 - p_2 f_2\right) \quad , \qquad\qquad (32)$$

$$\tilde{\Phi} = \left(p_1\varphi_1 - p_2\varphi_2\right) \quad . \qquad\qquad (33)$$

Superheterodyne signal $S_{\tilde{1}\times\tilde{2}}$ is therefore comprised of two sidebands, $S_{\tilde{1}\times\tilde{2}}^{+}$ and $S_{\tilde{1}\times\tilde{2}}^{-}$, of equal amplitude, one sideband with frequency $\tilde{\nu}$ and phase $\tilde{\vartheta}$ and a second sideband with frequency $\tilde{F}$ and phase $\tilde{\Phi}$.

Referring once again to FIG. **1d**, electronic processor **109B** preferably comprises processor **1093A** to separate the two sideband signals $S_{\tilde{1}\times\tilde{2}}^{+}$ and $S_{\tilde{1}\times\tilde{2}}^{-}$, using filtering or any of the like techniques for separating two signals that are separated in frequency. The frequency $\tilde{F}$ of the lower frequency sideband of the superheterodyne signal can be very much smaller than the frequency $\tilde{\nu}$ of the higher

46

frequency sideband of the superheterodyne signal as
subsequently described in the remaining discussion of the
third variant of the first embodiment, considerably
simplifying the separating task of processor **1093A**.

5   Electronic processor **109B** further comprises processors

1094F and **1094G** to determine the phases $\tilde{\vartheta}$ and $\tilde{\Phi}$ using
time-based phase detection such as a Hilbert transform
phase detector (see section 4.1.1 of "Phase-locked loops:
theory, design, and applications" by R. E. Best, *ibid.*) or

10   the like and the phases of the drivers **5** and **6**.

The phases of the drivers **5** and **6** are transmitted as
electrical signals in either digital or analog format,
preferably a digital format, for use as reference signals
101 and **102**, respectively, to electronic processor **109B**.

15   The reference signal for the determination of phases $\tilde{\vartheta}$

and $\tilde{\Phi}$ by way of phase sensitive detection is generated by
mixing reference signals **101** and **102** and high pass and low
pass filtering, respectively. Electronic processor **109B**
additionally comprises processor **1094A** to determine the

20   phase shift φ_1 using time-based phase detection or the
like, reference signal **101** serving as the reference signal
in phase sensitive detection.

Reference signals, alternatives to reference signals
101 and **102**, may also be generated by an optical pick off

25   means and detectors (not shown in figures) by splitting
off portions of beams **9** and **10** with beam splitters,
preferably non-polarizing beam splitters, mixing the
portion of the beam **9** and the portion of beam **10** that are
split off, and detecting the mixed portions to produce

30   heterodyne reference signals.

47

The quantities $p\tilde{\vartheta}$, $p\tilde{\Phi}$, $p\tilde{\xi}$, and pZ of the third variant of the first embodiment are formally the same as ϑ, Φ, ξ, and Z, respectively, of the first embodiment with $l_1 = p_1$ and $l_2 = p_2$. Thus, the refractivity $(n_1 - 1)$ of

5   the gas or changes in L due to the gas in the measuring path can be expressed in terms of other quantities obtained in the third variant of the first embodiment by use of the known relationships cited in this paragraph and by the use of Eqs. (11), (12), (13), (19), and (20) with

10 $l_1 = p_1$ and $l_2 = p_2$ as specified by Eqs. (24).

A preferred embodiment of the invention having been disclosed in the description of the third variant of the first embodiment, the underlying advantages of the third variant of the first embodiment will be made more clear by

15 the following discussion. It is evident from the calculation of the refractivity by Eq. (7) or the calculation of the effect of the refractivity of the gas on the optical path by Eq. (14), that the required accuracies to which the superheterodyne sideband phases $\tilde{\vartheta}$

20 and $\tilde{\Phi}$ must be determined are related to the values of the wavenumbers K and χ. In that the frequency $\tilde{F}$ can be very much smaller than the frequency $\tilde{v}$, and since it is generally easier to calculate the phase with high resolution of an electronic signal of lower frequency, it

25 is generally most advantageous to rely on a high-accuracy measurement of the superheterodyne sideband phase $\tilde{\Phi}$. This is readily achieved in the inventive apparatus when the wavenumbers K and χ are related according to Eq. (16), the calculation of the refractivity by Eq. (19) or

30 the calculation of the effect of the refractivity of the gas on the optical path by Eq. (20) substantially not

involving the superheterodyne sideband phase $\tilde{\vartheta}$. Further, the magnitude of the superheterodyne sideband phase $\tilde{\Phi}$ is less than the magnitude superheterodyne sideband phase $\tilde{\vartheta}$, less by a factor of approximately $(n_2 - n_1)/(n_2 + n_1)$ as

5   expressed by Eq. (17). This greatly improves in general the phase detection accuracy of the quantity $[\vartheta(K/\chi) - \Phi]$ that appears in Eqs. (7) and (14) and in particular for moving objects, such as are commonly encountered in microlithography equipment, which may be coupled to the

10   interferometric apparatus as at as at 267.

Eq. (18) also forms the basis for a conclusion that sources 1 and 2 need not be phase locked for the third variant of the first embodiment. Eq. (18) is actually a weak condition when viewed in terms of a phase-locked

15   requirement for sources 1 and 2. Consider for an example a desired precision of $\varepsilon \cong 3 \times 10^{-6}$ for measuring the refractivity $(n_1 - 1)$ of the gas or for the change in the optical path length of the measurement leg due to the gas, corresponding to a relative distance measuring precision

20   of approximately 1×10^{-9} in a distance measuring interferometer, $(n_1 - 1) \cong 3 \times 10^{-4}$, and $(n_2 - n_1) \cong 1 \times 10^{-5}$. For the example, the condition expressed by Eq. (18) written in terms of source frequencies ν_1 and ν_2 instead of wavelengths λ_1 and λ_2, respectively, is

25

$$\left| \nu_2 - \frac{p_1}{p_2} \nu_1 \right| \ll 3 \times 10^{-11} \nu_2 \qquad . \qquad\qquad (34)$$

49

For source wavelengths in the visible part of the spectrum and for low order integers for p_1 and p_2, Eq. (34) translates into a condition

$$\left| v_2 - \frac{p_1}{p_2} v_1 \right| \ll 30 \, \text{kHz} \qquad . \qquad\qquad (35)$$

The result expressed in Eq. (35) is clearly a significantly less restrictive condition on the frequencies of sources **1** and **2** than a phase-locked condition.

The remaining description of the third variant of the first embodiment is the same as corresponding portions of the descriptions given for the first embodiment.

It will be appreciated by those skilled in the art that alternative data processing may be considered for the third variant of the first embodiment without departing from the spirit and scope of the present invention. For example, it may prove useful to generate the modified heterodyne signals by electronically dividing time-dependent arguments $\alpha_1(t)$ and $\alpha_2(t)$ of heterodyne signals s_1 and s_2, respectively, by coefficients p_2 and p_1, respectively, so as to create two modified heterodyne signals $\tilde{s}_1'$ and $\tilde{s}_2'$ having the forms

$$\tilde{s}_1' = \tilde{A}_1' \cos\left[\alpha_1(t)/p_2\right] \qquad , \qquad\qquad (36)$$
$$\tilde{s}_2' = \tilde{A}_2' \cos\left[\alpha_2(t)/p_1\right] \qquad .$$

The dividing may be achieved by any one of the conventional frequency dividing techniques commonly known in the art, such as the use of phase-locked loops or

50

generation of a rectangle wave signal which changes sign at every other zero crossing of the signal whose argument is being divided by two. The subsequent description of the variant of the first embodiment based on modified

5   heterodyne signals $\tilde{s}_1'$ and $\tilde{s}_2'$ is the same as corresponding portions of the description of the third variant of the first embodiment based on modified heterodyne signals $\tilde{s}_1$ and $\tilde{s}_2$.

Another alternative data processing that may be

10   considered for the third variant of the first preferred embodiment without departing from the spirit and scope of the present invention is the addition of the modified heterodyne signals $\tilde{s}_1$ and $\tilde{s}_2$ together, rather than multiplying them as in the third variant of the first

15   embodiment, resulting in the expression:

$$S_A = \tilde{s}_1 + \tilde{s}_2 \quad . \quad\quad\quad\quad\quad\quad\quad\quad (37)$$

A superheterodyne signal would be obtained from S_A by

20   conventional techniques commonly known in the art such as square law detection or by signal rectification. (*cf.* Dändliker *et al.*, *ibid.*, and Redman and Wall, *ibid.*). Further, another alternative signal to $S_{\tilde{1}\times\tilde{2}}$ may be generated by selecting the appropriate term in the

25   binomial expansion of $(s_1 + s_2)^{p+q}$ through the use of phase sensitive detection.

Reference is now made to FIGS. **2a-2f** which depict in diagrammatic form the second preferred embodiment of the present invention for measuring and monitoring the

30   refractivity of a gas in a measurement path and/or the change in the optical path length of the measurement path

51

due to the gas wherein either or both the refractive index
of the gas and the physical length of the measurement path
may be changing and where the stability of the adopted
light sources is sufficient and the ratio of the

5   wavelengths of the light beams generated by the adopted
light sources is matched to a known ratio value with a
relative precision sufficient to meet the required
precision imposed on the output data by the final end use
application.

10   A preferred method for electronically processing the
heterodyne signals s_3 and s_4 is presented herewithin for
the case when l_1 and/or l_2 are not low order integers. For
the case when l_1 and l_2 are both low order integers and the
ratio of the wavelengths matched to the ratio (l_1/l_2) with a

15   relative precision sufficient to meet the required
precision imposed on the output data by the end use
application, the preferred procedure for electronically
processing the heterodyne signals s_1 and s_2 is the same as
the one subsequently set down for the second variant of

20   the first preferred embodiment of the present invention.
The second preferred embodiment of the present
invention is comprised of a set of differential plane
mirror interferometers, the first embodiment being
comprised of a polarized Michelson interferometer, wherein

25   the differential plane mirror interferometer is well
suited to requirements of micro-lithographic fabrication
of integrated circuits. The description of the sources of
light beams 9 and 10 and of light beams 9 and 10 for the
second embodiment is the same as the description of the

30   sources of light beams 9 and 10 and of light beams 9 and
10 given for the first preferred embodiment of the present
invention.

52

As illustrated in FIG. 2a, beam 9 is incident on differential plane mirror interferometer 69 and beam 10 is reflected by mirror 54 as beam 12 which is incident on differential plane mirror interferometer 70. Differential

5   plane mirror interferometers 69 and 70, beam splitter 65, and external mirrors furnished by external mirror system 90 comprise interferometric means for introducing a phase shift φ_3 between the x and y components of beam 9 and a phase shift φ_4 between the x and y components of beam 12.

10   A differential plane mirror interferometer measures the optical path changes between two external plane mirrors. In addition, it is insensitive to thermal and mechanical disturbances that may occur in the interferometer beam splitting cube and associated optical

15   components. Differential plane mirror interferometer 69 has four exit/return beams 17, 25, 117, and 125 as shown in FIG. 2b. Beams 17 and 25 originating from one frequency component of beam 9 comprise one measurement leg and beams 117 and 125 originating from a second frequency

20   component of beam 9 comprise a second measurement leg. Beams for which the first frequency component of beam 9 is the sole progenitor are indicated in FIG. 2b by dashed lines and beams for which the second frequency component of beam 9 is the sole progenitor are indicated in FIG. 2b

25   by dotted lines.

Differential plane mirror interferometer 70 has four exit/return beams 18, 26, 118, and 126 as shown in FIG. 2c. Beams 18 and 26 originating from one frequency component of beam 12 comprise one measurement leg and

30   beams 118 and 126 originating from a second frequency component of beam 12 comprise a second measurement leg.

Beams for which the first frequency component of beam **12** is the sole progenitor are indicated in FIG. **2c** by dashed lines and beams for which the second frequency component of beam **12** is the sole progenitor are indicated in FIG. **2c**

5   by dotted lines.

Beams **17**, **25**, **117**, and **125** are incident on beam splitter **65** and are transmitted by coating **66**, preferably a dichroic coating, as beams **E17**, **E25**, **E117**, and **E125**, respectively. Beams **E17**, **E25**, **E117**, and **E125** are incident

10   on external mirror system **90**, illustrated in FIG. **2d**, which results in beams **27** and **127** shown in FIG. **2b**. Beams **127** and **27** contain information at wavelength λ_1 about the optical path length through the gas in measuring path of external mirror system **90** and about the optical path

15   length through a reference path, respectively. Likewise, beams **18**, **26**, **118**, and **126** are incident on beam splitter **65** and reflected by dichroic coating **66** as beams **E18**, **E26**, **E118**, and **E126**, respectively. Beams **E18**, **E26**, **E118**, and **E126** are incident on external mirror system **90**,

20   illustrated in FIG. **2e**, which results in beams **28** and **128** shown in FIG. **2c**. Beam **128** contains information at wavelength λ_2 about optical path lengths through the gas in the measuring path of external mirror system **90** and beam **28** contains information at wavelength λ_2 about

25   optical path lengths through a reference path.

In FIG. **2b**, beam **27** is reflected by mirror **63B**, a portion of which is reflected by beam splitter **63A**, preferably a non-polarizing type, to become one component of beam **29**. A portion of beam **127** is transmitted by beam

30   splitter **63A** to become a second component of beam **29**. Beam **29** is a mixed beam, the first and second components

of beam **29** having the same linear polarizations. Beam **29**
exits the differential plane mirror interferometer **69**.

 Referring to FIG. **2c**, beam **28** is reflected by mirror
58B, a portion of which is reflected by beam splitter **58A**,
5 preferably a non-polarizing beam splitter, to become a
first component of beam **30**. A portion of beam **128** is
transmitted by beam splitter **58A** to become a second
component of beam **30**. Beam **30** is a mixed beam, the first
and second components of beam **30** having the same linear
10 polarizations.

 The magnitude of phase shifts φ_3 and φ_4 are related
to the difference L_i between the round-trip physical
length of path i of measurement path **98** and of reference
paths shown in FIGS. **2a-2e** according to the formulae
15

$$\varphi_3 = \sum_{i=1}^{i=p} \varphi_{3,i} = \sum_{i=1}^{i=p} L_i k_1 n_{1i} + \zeta_3 \quad ,$$

$$\varphi_4 = \sum_{i=1}^{i=p} \varphi_{4,i} = \sum_{i=1}^{i=p} L_i k_2 n_{2i} + \zeta_4 \quad ,$$

(38)

where n_{ji} are the refractive indices of gas in path i of
measurement path **98** corresponding to wavenumber k_j. The
20 nominal value for L_i corresponds to twice the spatial
separation of mirror surfaces **95** and **96** in external mirror
system **90** (cf. FIGS. **2d** and **2e**). The phase offsets ζ_j
comprise all contributions to the phase shifts φ_j that
are not related to the measurement path **98** or reference
25 paths. In FIGS. **2a-2e**, differential plane mirror
interferometers **69** and **70**, beam splitter **65**, and external
mirror system **90** are configured so that $p = 2$ so as to

illustrate in the simplest manner the function of the apparatus of the second preferred embodiment of the present invention.

Eqs. (38) are valid for the case where the paths for one wavelength and the paths for the second wavelength are substantially coextensive, a case chosen to illustrate in the simplest manner the function of the invention in the second embodiment. To those skilled in the art, the generalization to the case where the respective paths for the two different wavelengths are not substantially coextensive is a straight forward procedure.

Cyclic errors that produce nonlinearities in distance measuring interferometry (cf. the cited articles by Bobroff) have been omitted in Eqs. (38). The description of techniques known to those skilled in the art for either the reduction of the cyclic errors to negligible levels or for the compensation for the presence of cyclic errors is the same as corresponding portions of the description given for the first preferred embodiment.

In a next step as shown in FIG. **2a**, phase-shifted beams **29** and **30** impinge upon photodetectors **185** and **186**, respectively, resulting in two electrical interference signals, heterodyne signals s_3 and s_4, respectively, preferably by photoelectric detection. The signal s_3 corresponds to wavelength λ_1 and signal s_4 corresponds to the wavelength λ_2. The signals s_j have the form the same as that expressed by Eq. (3) with $j = 3$ and 4. Heterodyne signals s_3 and s_4 are transmitted to electronic processor **209** for analysis as electronic signals **203** and **204**, respectively, in either digital or analog format, preferably in digital format.

56

Referring now to FIG. 2f, electronic processor 209
preferably is comprised of alphameric numbered elements
wherein the numeric component of the alphameric numbers
indicate the function of an element, the same numeric

5   component/function association as described for the
electronic processing elements of the first embodiment
depicted in FIG. 1b. The description of the steps in
processing of the heterodyne signals s_3 and s_4 by
electronic processor 209 for phases ϑ and Φ is the same

10   as corresponding portions, according to the numeric
component of the alphameric numbers of elements, of the
description of steps in the processing of the heterodyne
signals s_1 and s_2 of the first embodiment by electronic
processor 109.

15   The phases φ_3, ϑ, and Φ created by electronic
processor 209 formally have the same properties as φ_1, ϑ,
and Φ, respectively, created by electronic processor 109
of the first embodiment. Thus, the refractivity $(n_1 - 1)$ of
the gas or changes in L due to the gas in the measuring

20   path can be expressed in terms of other quantities
obtained in the second embodiment by use of the known
relationships cited in this paragraph and by the use of
Eqs. (19) and (20).

The resolution of phase redundancy in φ_3 is required

25   in the computation of L using Eq. (20) and the resolution
of the phase redundancy in φ_3 is required in the
computation of changes L using Eq. (20) if χ is variable
in time. The resolution of the phase redundancy in φ_3,
if required, presents a problem similar to the one as

30   subsequently described with respect to the resolution of
phase redundancy in ϑ in the fourth embodiment of the

57

present invention. As a consequence, the procedures described for the resolution of phase redundancy in ϑ with respect to the fourth embodiment can be adapted for use in the resolution of the phase redundancy in φ_3.

5   The offset terms involving ζ_3 and Q that are present in Eqs. (19) and (20) and defined in Eqs. (2) and (11) are terms that may require determination and monitoring depending on whether the refractivity $(n_1 - 1)$ and/or L are being measured, whether changes in the refractivity $(n_1 - 1)$

10   and/or L are being measured, whether ζ_3 and/or Q are variable in time, and/or whether χ is variable in time. One procedure for the determination of ζ_3 and Q is based on replacement of mirror **91** of the external mirror system **90** with a mirror **R91** (not shown in FIGS. **2d** and **2e**) having

15   a surface **R93** corresponding to surface **93** of mirror **91** coated so as be a reflecting surface for both wavelengths λ_1 and λ_2 and measuring the resulting values of φ_3 and Φ. Let the resulting values of φ_3 and Φ be φ_{3R} and Φ_R, respectively. The quantities ζ_3 and Q are related to φ_{3R}

20   and Φ_R, respectively, as evident from Eqs. (2) and (19) by the formulae

$$\zeta_3 = \varphi_{3R} \qquad , \tag{39}$$

25
$$Q = -\Phi_R \qquad . \tag{40}$$

The non-electronic contributions to ζ_3 and Q should be substantially constant in time because of the significant level of compensation that takes place in the differential

30   plane mirror interferometers **69** and **70**, beam splitter **65**,

58

and external mirror system **90**. The electronic
contributions to ζ_3 and Q may be monitored by purely
electronic means (not shown).

    It will be apparent to someone skilled in the art
5   that as a consequence of the incorporation of beam
splitter **65** in the second preferred embodiment, polarizing
coating **73** of beam splitter **71** and quarter-wave
retardation plate **77** need only meet performance
specifications at λ_1 while polarizing coating **74** of beam
10   splitter **72** and quarter-wave retardation plate **78** need
only meet performance specifications at λ_2. This
assignment of critical operations according to wavelength
as disclosed in the second embodiment is an important
aspect of the present invention, particularly in
15   applications requiring precision such as the case of
micro-lithographic fabrication of integrated circuits.
However, the assignment of operations according to
wavelength need not done as disclosed in the second
preferred embodiment, *e.g.* the function of beam splitters
20   **71** and **72** being achieved by a single beam splitter with an
appropriately modified polarizing surface, without
departing from the spirit or scope of the present
invention.

    FIG. **2b** depicts in schematic form one embodiment of
25   the differential plane mirror interferometer **69** shown in
FIG. **2a**. It operates in the following way: beam **9** is
incident on beam splitter **55A**, preferably a polarizing
beam splitter, with a portion of beam **9** being transmitted
as beam **13**. A second portion of beam **9** is reflected by
30   beam splitter **55A**, subsequently reflected by mirror **55B**,
and then transmitted by half-wave phase retardation plate
79 as beam **113**, the half-wave phase retardation plate **79**

rotating by 90° the plane of polarization of the second portion of beam **9** reflected by beam splitter **55A**. Beams **13** and **113** have the same polarizations but still have different frequencies. The function of beam splitter **55A**

5   and mirror **55B** is to spatially separate the two frequency components of beam **9** using conventional polarization techniques.

Beams **13** and **113** enter polarizing beam splitter **71**, which has a polarizing coating **73**, and are transmitted as

10   beams **15** and **115**, respectively. Beams **15** and **115** pass through quarter-wave phase retardation plate **77** and are converted into circularly polarized beams **17** and **117**, respectively. Beams **17** and **117** are transmitted by beam splitter **65** with dichroic coating **66**, reflected back on

15   themselves by mirrors within external mirror system **90** as illustrated in FIG. **2d**, pass back through beam splitter **65**, and subsequently pass back through quarter-wave retardation plate **77** and converted into linearly polarized beams that are orthogonally polarized to the original

20   incident beams **15** and **115**. These beams are reflected by polarizing coating **73** to become beams **19** and **119**, respectively. Beams **19** and **119** are reflected by retroreflector **75** to become beams **21** and **121**, respectively. Beams **21** and **121** are reflected by

25   polarizing coating **73** to become beams **23** and **123**, respectively. Beams **23** and **123** pass through quarter-wave phase retardation plate **77** and are converted into circularly polarized beams **25** and **125**, respectively. Beams **25** and **125** are transmitted by beam splitter **65**,

30   reflected back on themselves by mirrors within external mirror system **90** as illustrated in FIG. **2d**, pass back

through beam splitter **65**, and subsequently pass back
through quarter-wave retardation plate **77** and converted
into linearly polarized beams, the linear polarizations
being the same as the linear polarizations of the original
5   incident beams **15** and **115**. These beams are transmitted by
polarizing coating **73** to become beams **27** and **127**,
respectively.

Beam **27** is reflected by mirror **63B**, and then a
portion reflected by beam splitter **63A**, preferably a non-
10 polarizing type, as a first component of beam **29**. Beam
127 is incident on beam splitter **63A** with a portion of
beam **127** being transmitted as a second component of beam
29, the first and second components of beam **29** having the
same linear polarizations but still having different
15 frequencies. Phase-shifted beam **29** is a mixed beam, the
first and second components of beam **29** having the same
linear polarizations.

FIG. **2c** depicts in schematic form one embodiment of
differential plane mirror interferometer **70** shown in FIG.
20 **2a**. It operates in the following way: Beam **12** is incident
on beam splitter **56A**, preferably a polarizing beam
splitter, with a portion of beam **12** being transmitted as
beam **14**. A second portion of beam **12** is reflected by beam
splitter **56A**, subsequently reflected by mirror **56B**, and
25 then transmitted by half-wave phase retardation plate **80**
as beam **114**, the half-wave phase retardation plate **80**
rotating by 90° the plane of polarization of the second
portion of beam **12** reflected by beam splitter **56A**. Beams
14 and **114** have the same polarizations but still have
30 different frequencies. The function, in part, of beam
splitter **56A** and mirror **56B** is to spatially separate the

61

two frequency components of beam **12** using conventional
polarization techniques.

Beams **14** and **114** enter polarizing beam splitter **72**,
which has a polarizing coating **74**, and are transmitted as
5   beams **16** and **116**, respectively. Beams **16** and **116** pass
through quarter-wave phase retardation plate **78** and are
converted into circularly polarized beams **18** and **118**,
respectively. Beams **18** and **118** are reflected by beam
splitter **65** with dichroic coating **66**, reflected back on
10   themselves by mirrors within external mirror system **90** as
illustrated in FIG. **2e**, reflected by surface **66** of beam
splitter **65** a second time, and subsequently pass back
through quarter-wave retardation plate **78** and converted
into linearly polarized beams that are orthogonally
15   polarized to the original incident beams **16** and **116**.
These beams are reflected by polarizing coating **74** to
become beams **20** and **120**, respectively. Beams **20** and **120**
are reflected by retroreflector **76** to become beams **22** and
122, respectively. Beams **22** and **122** are reflected by
20   polarizing coating **74** to become beams **24** and **124**,
respectively. Beams **24** and **124** pass through quarter-wave
phase retardation plate **78** and are converted into
circularly polarized beams **26** and **126**, respectively.
Beams **26** and **126** are reflected by surface **66** of beam
25   splitter **65**, reflected back on themselves by mirrors
within external mirror system **90** as illustrated in FIG.
2e, reflected by surface **66** of beam splitter **65** a second
time, and subsequently pass back through quarter-wave
retardation plate **78** and converted into linearly polarized
30   beams, the same linear polarizations as the linear
polarizations of the original incident beams **16** and **116**.

These beams are transmitted by polarizing coating **74** to become beams **28** and **128**, respectively. Beams **28** and **128** contain information at wavelength λ_2 about the optical path lengths through the gas in measurement path **98**

5   wherein the effects of the refractivity of the gas is to be determined and about the optical path lengths through the reference leg, respectively.

Beam **28** is reflected by mirror **58B**, and then a portion reflected by beam splitter **58A**, preferably a non-

10   polarizing type, as a first component of beam **30**. Beam **128** is incident on beam splitter **58A** with a portion of beam **128** being transmitted as a second component of beam **30**, the first and second components of beam **30** having the same linear polarizations but still having different

15   frequencies. Phase-shifted beam **30** is a mixed beam, the first and second components of beam **30** having the same linear polarizations.

The remaining description of the second preferred embodiment is the same as corresponding portions of the

20   description given for the first preferred embodiment.

There are three variants of the second embodiment wherein the description of each of the three variants of the second embodiment is the same as corresponding portions of descriptions given for the three variants of

25   the first preferred embodiment.

The description of the first preferred embodiment noted that the configuration of interferometer illustrated in FIG. **1a** is known in the art as a Michelson interferometer. The description of the second preferred

30   embodiment noted that the configuration of interferometers illustrated in FIGS. **2a-2e** are known in the art as differential plane mirror interferometers. Other forms of

63

the differential plane mirror interferometer and forms of
other interferometers such as the plane mirror
interferometer or the angle-compensating interferometer or
similar device such as is described in an article entitled
5   "Differential interferometer arrangements for distance and
angle measurements: Principles, advantages and
applications" by C. Zanoni, *VDI Berichte* Nr. **749**, 93-106
(1989), is preferably incorporated into the apparatus of
the first embodiment of the present invention as when
10   working with stages commonly encountered in the micro-
lithographic fabrication of integrated circuits without
significantly departing from the spirit and scope of the
present invention.

The third and fourth preferred embodiments of the
15   present invention and variants thereof, illustrated in
FIGS. **3a-3b** and **4a-4c**, respectively, are embodiments to
measure a refractivity of a gas and/or the change in the
optical path length of a measurement path due to the gas
when the condition set fourth in Eq. (18) for the first
20   and second preferred embodiments and variants thereof is
not satisfied, *i.e.*

$$\left| \frac{\lambda_1}{\lambda_2} - \frac{l_1}{l_2} \right| \not\ll \left(\frac{l_2}{l_1} \right) (n_2 - n_1)\varepsilon \qquad . \tag{41}$$

25   Under the condition set fourth in Eq. (41), the
approximate ratio, preferably the ratio (K/χ), must be
either known or measured in accordance with Eqs. (7) and
(14) for the third and fourth embodiments and variants
thereof in addition to already described quantities in
30   order to achieve the required accuracy in the
determination of a refractivity of the gas and/or the

64

change in the optical path of the measurement path due to the gas.

Each of the first and second preferred embodiments and variants thereof can be converted from an apparatus and method for measuring a refractivity of the gas and/or the change in the optical path of the measurement path due to the gas to an apparatus and method for measuring χ and/or the ratio (K/χ). The conversion, as demonstrated in the following descriptions, is accomplished by changing the measurement legs of the first and second embodiments and variants thereof so that the measuring paths through a gas in respective measurement paths **298** and **98** are replaced by a predetermined medium, preferably a vacuum, and the respective measurement legs have a fixed physical length. Accordingly, the third embodiment and variants thereof are each comprised of an unmodified and a modified apparatus and method from the first embodiment or a variant thereof and the fourth embodiment and variants thereof are each comprised of an unmodified and a modified apparatus and method from the second embodiment of a variant thereof, the modified apparatus and method being comprised of the respective unmodified apparatus and method with a modified measurement leg.

Reference is now made to FIGS. **3a-3b** that depict in diagrammatic form the third preferred embodiment of the present invention. The description of the source of light beam **9** of the third embodiment is the same as that for light beam **9** of the first preferred embodiment and the description of the source of light beam **10** of the third embodiment is the same as that for light beam **10** of the first preferred embodiment except that the condition on wavelengths λ_1 and λ_2 expressed by Eq. (18) is replaced

65

by the condition set fourth in Eq. (41). Light beam **9** is reflected by mirror **253A** and a first portion reflected by beam splitter **253B**, preferably a non-polarizing type, to become one component of beam **213**, the λ_1 component. A

5   second portion of beam **9** reflected by mirror **253A** is transmitted by beam splitter **253B** and reflected by mirror **253c** to become one component of beam **213b**, the λ_1 component. Light beam **10** is incident on beam splitter **253B** and a first portion transmitted to become a second

10   component of beam **213**, the λ_2 component. A second portion of beam **10** is reflected by beam splitter **253B** and reflected by mirror **253c** to become a second component of beam **213b**, the λ_2 component (see FIG. **3a**). The λ_1 and λ_2 components of beams **213** and **213b** are preferably parallel

15   and coextensive, respectively.

Because of the requirement in the third preferred embodiment to measure χ and/or the ratio (K/χ), the third preferred embodiment as described in a preceding paragraph is comprised in part of the same apparatus and method as

20   for the first preferred embodiment and of additional means for determination of χ and/or the ratio (K/χ). The additional means for determination of χ and/or the ratio (K/χ) is the same as the apparatus and method of the first preferred embodiment except for the measurement path **298**.

25   Consequently, a number of elements of the apparatus shown in FIGS. **3a-3b** for determination of χ and/or the ratio (K/χ) perform analogous operations as apparatus for determination of a refractivity of a gas and/or the change in the optical path length of a measurement path due to

30   the gas of the first preferred embodiment, apart from the

66

suffix "**b**" when referring to apparatus for determination of χ and/or the ratio (K/χ).

The description of interferometer **260b** is the same as that for interferometer **260** except with respect to the gas

5   in measurement path **298b** and the round-trip physical length of the measurement path **298b**. The measurement leg in the interferometer **260b** of the third preferred embodiment includes measurement path **298b** as illustrated in FIGS. **3a**, measurement path **298b** preferably being an

10   evacuated volume of fixed length $(L_b/2)$.

The differences in the measurement path **298b** and **298** lead to modifications of Eqs. (2) such that the magnitude of phase shifts φ_{1b} and φ_{2b}, counterparts to phase shifts φ_1 and φ_2, respectively, are related to the round-trip

15   physical length L_b of measurement path **298b** and to reference paths as shown in FIG. **3a** according to the formulae

$$\varphi_{jb} = L_b p k_j + \zeta_{jb} \quad , \quad j = 1 \text{ and } 2 \quad . \tag{42}$$

20

In a next step as shown in FIG. **3a**, phase-shifted beams **217b** and **218b** impinge upon photodetectors **85b** and **86b**, respectively, resulting in two interference signals, heterodyne signals s_{1b} and s_{2b}, respectively, preferably by

25   photoelectric detection. The signal s_{1b} corresponds to wavelength λ_1 and signal s_{2b} corresponds to the wavelength λ_2. The signals s_{jb} have the form

67

$$s_{jb} = A_{jb} cos\left[\alpha_{jb}(t)\right] \qquad , \qquad j = 1 \text{ and } 2 \quad , \qquad (43)$$

where the time-dependent arguments $\alpha_{jb}(t)$ are given by

5
$$\alpha_{jb}(t) = 2\pi f_j t + \varphi_{jb} \qquad , \qquad j = 1 \text{ and } 2 \quad . \qquad (44)$$

Heterodyne signals s_{1b} and s_{2b} are transmitted to
electronic processor **109b** for analysis as electronic
signals **103b** and **104b**, respectively, in either digital or
10 analog format, preferably in digital format.

A preferred method for electronically processing the
heterodyne signals s_{1b} and s_{2b} is presented herewithin for
the case when l_1 and/or l_2 are not low order integers. For
the case when l_1 and l_2 are both low order integers and the
15 ratio of the wavelengths matched to the ratio (l_1/l_2) with a
relative precision sufficient to meet the required
precision imposed on the output data by the end use
application, the preferred procedure for electronically
processing the heterodyne signals s_1 and s_2 is the same as
20 the one subsequently set down for the third variant of the
third preferred embodiment of the present invention.

Referring now to FIG. **3b**, electronic processor **109b**
further comprises electronic processors **1094Ab** and **1094Bb**
to determine the phases φ_{1b} and φ_{2b}, respectively, by
25 either digital or analog signal processes, preferably
digital processes, using time-based phase detection such
as a digital Hilbert transform phase detector [R. E. Best,
ibid.] or the like and the phase of drivers **5** and **6**.

Referring again to FIG. **3b**, the phase φ_{1b} and the
30 phase φ_{2b} are next multiplied by l_1/p and l_2/p,

68

respectively, in electronic processors **1095Ab** and **1095Bb**, respectively, preferably by digital processing, resulting in phases $(l_1/p)\varphi_{1b}$ and $(l_2/p)\varphi_{2b}$, respectively. The phases $(l_1/p)\varphi_{1b}$ and $(l_2/p)\varphi_{2b}$ are next added together in electronic

5 processor **1096Ab** and subtracted one from the other in electronic processor **1097Ab**, preferably by digital processes, to create the phases ϑ_{1b} and Φ_{1b}, respectively. Formally,

10
$$\vartheta_{1b} = \left(\frac{l_1}{p}\varphi_{1b} + \frac{l_2}{p}\varphi_{2b} \right) \quad , \qquad\qquad (45)$$

$$\Phi_{1b} = \left(\frac{l_1}{p}\varphi_{1b} - \frac{l_2}{p}\varphi_{2b} \right) \quad . \qquad\qquad (46)$$

The phases ϑ_{1b} and Φ_{1b} are transmitted to computer **110** as

15 signals **105b**, in either digital or analog format, preferably in digital format.

The quantities χ and K are related to phase ϑ_b and phase Φ_b according to the formulae

20
$$\chi = (\vartheta_b - \xi_b)/(2L_b) \quad , \qquad\qquad (47)$$

$$K = (\Phi_b - Z_b)/(2L_b) \quad , \qquad\qquad (48)$$

where

25
$$\xi_{2b} = \left(\frac{l_1}{p}\zeta_{1b} + \frac{l_2}{p}\zeta_{2b} \right) \quad , \qquad\qquad (49)$$

$$Z_{2b} = \left(\frac{l_1}{p} \zeta_{1b} - \frac{l_2}{p} \zeta_{2b} \right) \qquad . \qquad (50)$$

Eqs. (47) and (48) show that within a multiplicative factor $[1/(2L_b)]$ and phase offset terms ξ_b and Z_b, χ and K

5   are equal to the phase ϑ_b and the phase Φ_b, respectively. The ratio (K/χ) can be expressed by the formula

$$\frac{K}{\chi} = \frac{(\Phi_b - Z_b)}{(\vartheta_b - \xi_b)} \qquad (51)$$

10   using Eqs. (47) and (48). Therefore the ratio (K/χ) is obtained by substantially dividing Φ_b by ϑ_b without the requirement for an accurate measurement of L to the same precision as required for (K/χ). The phase redundancy of Φ_b can be determined as part of the same procedure used

15   to remove the phase redundancy of Φ in the unmodified apparatus and method of the first preferred embodiment incorporated as part of the third preferred embodiment.

The determination of the phase offsets ξ_b and Z_b is a problem similar to the one described with respect to the

20   determination of ξ_b and Z_b in the fourth preferred embodiment. As a consequence, the procedures described for the determination of ξ_b and Z_b with respect to the fourth embodiment can be adapted for determination of ξ_b and Z_b in the third embodiment.

25   The refractivity of the gas and/or the change in the optical path length of a measurement path due to the gas is subsequently obtained using Eqs. (7) and/or (14),

70

respectively. Because of the non-negligible effect of ϑ in Eqs. (7) and (14), the phase redundancy of ϑ must also be resolved in addition to the resolution of the phase redundancy of ϑ_b. The remainder of the description of

5   the third preferred embodiment is the same as that given for corresponding aspects of the first preferred embodiment except with respect to the description of the procedure for the resolution of the phase redundancies of ϑ and of ϑ_b. The resolution of the phase redundancies in

10   ϑ and ϑ_b is a problem similar to the one as subsequently described with respect to the required resolution of phase redundancy in ϑ and ϑ_b in the fourth embodiment of the present invention. As a consequence, the procedures described for the resolution of phase redundancies in ϑ

15   and ϑ_b with respect to the fourth embodiment can be adapted for use in the resolution of the phase redundancies in ϑ and ϑ_b for the third embodiment.

There are three variants of the third embodiment wherein the description of each of the three variants of

20   the third embodiment is the same as the description given for corresponding portions of the three variants of the first preferred embodiment.

Reference is now made to FIGS. **4a-4c** which depict in diagrammatic form the fourth preferred embodiment of the

25   present invention. The description of the source of light beams **9** and **9b** of the fourth embodiment is the same as that for light beam **9** of the second preferred embodiment and the description of the source of light beams **10** and **10b** of the fourth embodiment is the same as that for light

30   beam **10** of the second preferred embodiment except that the condition on wavelengths λ_1 and λ_2 expressed by Eq. (18)

71

is replaced by the condition set fourth in Eq. (41).

Light beams **9** and **9b** of the fourth embodiment are derived from a common light beam by beam splitter **153A**, preferably a non-polarizing type, and mirror **153B** and light beams **10**

5 and **10b** of the fourth embodiment are derived from a common light beam by beam splitter **154A**, preferably a non-polarizing type, and mirror **154B** (see FIG. **4a**).

Because of the requirement in the fourth preferred embodiment to measure χ and/or the ratio (K/χ), the fourth

10 preferred embodiment is comprised in part of the same apparatus and method as for the second preferred embodiment and of additional means for determination of χ and/or the ratio (K/χ). The additional means for determination of χ and/or the ratio (K/χ) is the same as

15 the apparatus and method of the second preferred embodiment except for the external mirror system **90b**. Consequently, a number of elements of the apparatus shown in FIGS. **4a-4c** for determination of χ and/or the ratio (K/χ) perform analogous operations as apparatus for

20 determination of a refractivity of a gas and/or the change in the optical path length of a measurement path due to the gas of the second preferred embodiment, apart from the suffix "b" when referring to apparatus for determination of χ and/or the ratio (K/χ).

25 The external mirror system **90b** of the fourth preferred embodiment is shown in FIGS. **4b** and **4c**. The description of external mirror system **90b** is the same as that for external mirror system **90** except with respect to the gas in the measurement path **98** and the round-trip

30 physical length of the measurement path **98**. The

measurement leg in the external mirror system **90b** of the

fourth preferred embodiment includes measurement path **98b**

as illustrated in FIGS. **4b** and **4c**, measurement path **98b**

preferably being an evacuated volume defined by mirrors

5   **91b** and **92b** and a cylinder **99b** of fixed length $\left(L_b/2\right)$.

Referring to FIGS. **4b** and **4c**, surface **95b** is coated so as

to reflect with high efficiency beams **E17b**, **E25b**, **E18b**,

and **E26b** and to transmit with high efficiency beams **E117b**,

E125b, **E118b**, and **E126b**. Surface **96b** is coated to reflect

10   with high efficiency beams **E117b**, **E125b**, **E118b**, and **E126b**.

The differences in the external mirror systems **90b**

and **90** lead to modifications of Eqs. (38) such that the

magnitude of phase shifts φ_{3b} and φ_{4b}, counterparts to

phase shifts φ_3 and φ_4, respectively, are related to the

15   round-trip physical length L_{bi} of path i of measurement

path **98b** and to reference paths as shown in FIGS. **4b** and

4c according to the formulae

$$\varphi_{1b} = \sum_{i=1}^{i=p} L_{bi}k_1 + \zeta_{1b} \quad ,$$

$$\varphi_{2b} = \sum_{i=1}^{i=p} L_{bi}k_2 + \zeta_{2b} \quad .$$

(52)

20

For those applications where changes in the

measurement path can be measured interferometrically, a

feature for example of an application based on a distance

measuring interferometer employed for measuring changes in

25   the measurement path (*c.f.* the second preferred

embodiment), the phase redundancy in ϑ can be resolved by

recording the change in ϑ as the movable mirror **92** of the

external mirror system **90** is scanned in a controlled

73

manner by translator **67** over a given length from a null position, the null position being the position where the physical lengths of the measurement and reference legs are the substantially the same. The accuracy required for the
5   determination of the null position is typically less accurate than the accuracy required for other parameters as exemplified in the following example: for $\lambda_1 = 0.633$ μm, $(n_1 - 1) \cong 3 \times 10^{-4}$, $(n_2 - n_1) \cong 1 \times 10^{-5}$, $\varepsilon \cong 10^{-9}$, and the condition set fourth in Eq. (17), the desired accuracy for the null
10   position determination corresponds to an uncertainty in ϑ of the order of ± 3.

For those applications where the determination of the refractivity and/or or the change in the optical path length due to the gas in a measurement leg is made and
15   mirror **92** of the external mirror system does not have a scanning capability such as considered in the preceding paragraph, other procedures are available for the resolution of the phase redundancies of ϑ and ϑ_b. The effective wavelengths of ϑ and ϑ_b are substantially the
20   same so that only procedures for the resolution of phase redundancy in either ϑ or ϑ_b need be described.

The second procedure described for the resolution of the phase redundancy of Φ in the description of the second embodiment can be adapted for the resolution of the
25   phase redundancies of ϑ_b, the second procedure being based on the use of a series of external mirror systems of type **90b** where the series of round-trip physical lengths of the series of external mirror systems form a geometric progression. The smallest or first round-trip physical
30   length in the series of round-trip physical lengths will be approximately $\lambda_1/8$ divided by the relative precision

that the initial value of ϑ_b is known. The second round-
trip physical length in the series of round-trip physical
lengths will be approximately the length of the first
round-trip physical length in the series of round-trip

5   physical lengths divided by the relative precision that
ϑ_b is measured using the first round-trip physical length
in the series of round-trip physical lengths. This is
again a geometric progression procedure, the resulting
series of round-trip physical lengths forming a geometric

10 progression, which is continued until the physical length
of the external mirror system **90b** used to measure the
refractivity or the change in optical path length due to
the refractivity of the gas would be exceeded if the
number in the series of round-trip physical lengths were

15 incremented by one. For the resolution of phase
redundancy in ϑ_b, a typical round-trip physical length
for the first round-trip physical length in the series of
round-trip physical lengths is of the order of 0.5 mm, a
typical round-trip physical length for the second round-

20 trip physical length in the series of round-trip physical
lengths is of the order of 50 mm, and a typical round-trip
physical length for a third round-trip physical length in
the series of round-trip physical lengths if required is
of the order of 5000 mm. The physical lengths in the

25 series of physical lengths used for the resolution of
phase redundancy in Φ_b are typically orders of magnitude
larger than the physical lengths in the series of physical
lengths used for the resolution of phase redundancy in
ϑ_b.

30   A third procedure is based upon the use of a source
(not shown in FIGS. **4a-4c**) of a series of known
wavelengths and measuring ϑ_b for these wavelengths. The

75

number of known wavelengths required for the resolution of the phase redundancy is generally comprised of a small set.

Another procedure to resolve the phase redundancy in ϑ_b is to observe the changes in ϑ_b as the measuring path 98b is changed from gas to an evacuated state (the vacuum pump and requisite gas handling system are not shown in FIGS. 4a-4c). The problems normally encountered in measuring absolute values for refractivity and changes in the optical path length due to the refractivity of the gas based in part on changing the gas pressure from a non-zero value to a vacuum are not present in the third preferred embodiment because of a relatively large uncertainty of the order of ± 3 typically permitted in the determination of ϑ_b.

The offset terms ξ_b and Z_b that are present in Eq. (51) and defined in Eqs. (47) and (48), respectively, are terms that may require determination and may require monitoring if variable in time. One procedure for the determination of ξ_b and Z_b is based on replacement of mirror 91b of the external mirror system 90b with a mirror Z91b (not shown in FIGS. 4a-4c) having a surface Z93b corresponding to surface 93b of mirror 91b coated so as be a reflecting surface for both wavelengths λ_1 and λ_2 and measuring the resulting ϑ_b and Φ_b. Let the resulting values of ϑ_b and Φ_b be ϑ_{bR} and Φ_{bR}, respectively. The quantities ξ_b and Z_b are related to ϑ_{bR} and Φ_{bR}, respectively, as evident from Eqs. (47) and (48) by the formulae

$$\xi_b = \vartheta_{bR} \qquad , \qquad\qquad\qquad (53)$$

$$Z_b = \Phi_{,bR} \qquad . \qquad\qquad\qquad (54)$$

The non-electronic contributions to ξ_b and Z_b should be substantially constant in time because of the significant level of compensation that takes place in the differential plane mirror interferometers **69b** and **70b**, beam splitter **65b**, and external mirror system **90b**. The electronic contributions to ξ_b and Z_b are monitored by purely electronic means (not shown).

The wavenumber χ is calculated by the computer using Eq. (47) and the measured values for ϑ_b and ξ_b. The ratio K/χ is calculated by the computer using Eq. (51).

The refractivity of a gas and/or the change in the optical path length of a measurement path due to the gas is subsequently obtained using Eqs. (7) and/or (14), respectively. The remainder of the description of the fourth preferred embodiment is the same as that given for corresponding portions of the second and third preferred embodiments.

There are three variants of the fourth embodiment wherein the description of each of the three variants of the fourth embodiment is the same as the description given for corresponding portions of the three variants of the second preferred embodiment.

It will be appreciated by those skilled in the art that the wavelength λ_1 of the light beam used for the determination of φ_1 in Eqs. (14) and (20) may be different from both of the two wavelengths used to determine the change in the optical path length of the

77

measuring path due to gas in the measuring path without departing from the scope and spirit of the present invention. The requisite reciprocal dispersive power Γ_3 would be defined in terms of the indices of refraction n_1,

5   n_2, and n_3 of the gas at the three wavelengths λ_1, λ_2, and λ_3, respectively, according to the formula

$$\Gamma_3 = \frac{(n_1 - 1)}{(n_3 - n_2)} \tag{55}$$

10   for $\lambda_3 < \lambda_2$.

It will be further appreciated by those skilled in the art that the two frequency components of either or both beams 9 and 10 may be spatially separated at any point following the means for introducing the frequency

15   shifts and prior to entering the respective interferometers of the described preferred embodiments without departing from the scope and spirit of the present invention. If the two frequency components of the either of the two beams are spatially separated for any

20   significant distance from the respective interferometer, it may be necessary to employ alternative reference beams such as described in the first embodiment.

It will also be appreciated by those skilled in the art that the differential plane mirror interferometer and

25   the external mirror system of the additional means for the determination of χ and/or the ratio (K/χ) in the fourth preferred embodiment may be configured such that one of the light beams corresponding to one of the wavelengths may enter and exit from one end of the external mirror

30   system and a second of the light beams corresponding to a

differing second wavelength may enter and exit from an
opposite end of the external mirror system in contrast to
the same end as disclosed in the fourth preferred
embodiment without departing from the scope or spirit of

5   the invention as defined in the claims. With the
reconfiguring of the external mirror system, beam splitter
65b may obviously be omitted, the light beams of differing
wavelengths entering and exiting through the mirrors **91b**
and **92b** with the reflecting and transmitting coatings on

10   mirror surfaces **95b** and **96b** having been reconfigured
accordingly.

The illustrations in FIGS. **2a-2e** and **4a-4c** depict two
preferred embodiments of the present invention wherein all
of the optical beams for an embodiment are in a single

15   plane. Clearly, modifications using multiple planes can
be made to one or more of the two preferred embodiments
and variants thereof without departing from the scope and
spirit of the invention.

The second and fourth preferred embodiments of the

20   present invention have external mirror systems **90b** and/or
90 wherein the measurement paths for λ_1 and λ_2 have the
same round-trip physical lengths and the reference paths
for λ_1 and λ_2 have the same round-trip physical lengths.
It will be appreciated by those skilled in the art that

25   the measurement paths for λ_1 and λ_2 can have different
physical lengths and the reference paths for λ_1 and λ_2
can have different physical lengths without departing from
the scope and spirit of the present invention as defined
in the claims. It will be further appreciated by those

30   skilled in the art that the measurement paths for λ_1 and
λ_2 can be physically displaced one from the other and the

79

reference paths for λ_1 and λ_2 can be physically displaced one from the other without departing from the scope and spirit of the present invention as defined in the claims although there may be some degradation in performance with

5   regard frequency response of the embodiments and/or in accuracy of calculated quantities due to for example spatial gradients in the refractivity of a gas in a measurement path.

It will be appreciated by those skilled in the art

10   that alternative data processing may be considered for the four preferred embodiments and variants thereof of the present invention without departing from the spirit and scope of the present invention.

The four preferred embodiments and variants thereof

15   of the present invention are all configured for use of heterodyne detection. It will be appreciated by those skilled in the art that homodyne detection can be employed in each of the four preferred embodiments and variants thereof without departing from the scope and spirit of the

20   present invention as defined in the claims. Homodyne receivers would be employed such as disclosed in commonly owned U.S. Pat. No. 5,663,793 entitled "Homodyne Interferometric Receiver and Method," issued Sept. 2, 1997 in the name of P. de Groot. The computation of the

25   refractivity of a gas and/or the change in the optical path length of a measurement path due to the gas would be obtained for example in the homodyne version of the first preferred embodiment directly from homodyne phases φ_{1H} and φ_{2H}, the homodyne phases φ_{1H} and φ_{2H} being counterparts to

30   phases φ_1 and φ_2 of the first preferred embodiment, and with homodyne versions of Eqs. (7) and (14).

The third and fourth preferred embodiments of the
present invention measure the ratio (K/χ) and/or χ and use
the measured values of (K/χ) and/or χ in the computation
of the refractivity of a gas and/or the change in the

5   optical path length of a measurement path due to the gas.
It will be appreciated by those skilled in the art that
the measured values of (K/χ) and/or χ can be used as error
signals in a feedback system such the condition expressed
by Eq. (18) is satisfied and/or such that χ is constant

10   without departing from the scope and spirit of the present
invention as defined in the claims. The measured value of
(K/χ) and/or χ in the feedback system are sent to either
source 1 and/or source 2 and used to control the
respective wavelengths of either source 1 and/or source 2,

15   for example by controlling the injection current and/or
temperature of a diode laser or the cavity frequency of an
external cavity diode laser.
It will be appreciated by those skilled in the art
that combinations of the means of the third and fourth

20   preferred embodiments to measure the ratio (K/χ) and/or χ
and of the means of the first and second preferred
embodiments may be used to determine the refractivity of a
gas and/or the change in the optical path length of a
measurement path due to the gas other than the

25   combinations used in the third and fourth preferred
embodiments without departing from the scope or spirit of
the invention as defined in the claims.
Reference is now made to FIG. 5 which is a
generalized flowchart depicting via blocks 500-526 various

30   steps for practicing an inventive method for measuring and
monitoring the refractivity of a gas in a measurement path

81

and/or the change in the optical path length of the
measurement path due to the gas wherein the refractivity
of the gas may be changing and/or the physical length of
the measurement path may be changing. While it will be

5   evident that the inventive method depicted in FIG. 5 may
be carried out using the inventive apparatus disclosed
hereinabove, it will also be apparent to those skilled in
the art that it may also be implemented with apparatus
other than that disclosed. For example, it will be

10   apparent that one need not use differential plane mirror
interferometers such as that used in the preferred
embodiments, but rather may use other conventional
interferometric arrangements so long as the required
reference and measurement legs are present. In addition,

15   it will be evident that one may use either a homodyne
approach or one in which heterodyning techniques are
advantageously employed. As will be further appreciated,
many of the steps in FIG. 5 may be carried out via
appropriate software run on a general purpose computer or

20   a suitably programmed microprocessor either of which may
be used to control other elements of the system as needed.

As seen in FIG. 5, one starts in block **500** by
providing two or more light beams having different
wavelengths which preferably have an approximate

25   approximate relationship as previously described. In
block **502**, the light beams are separated into components
which in block **504** are preferably altered by either
polarization or spatial encoding, or frequency shifting or
both. Otherwise, the light beams may simply be left

30   unaltered and passed through to block **506**.

As shown in blocks **522** and **524**, the relationship of
the wavelengths of the light beams may be monitored and if
their wavelengths are not within the limits previously

discussed, one can adopt corrective measures to compensate from departures of the relationship of the wavelengths from the desired relationship of the wavelengths. Either the departures can be used to provide feedback to control

5 the wavelengths of the light beam sources or corrections can be established and used in subsequent calculations which are influenced by departures or some combination of both approaches can be implemented.

In parallel or contemporaneously with generating the

10 light beams in block **500**, one also provides as indicated in block **526** an interferometer having two legs, a reference leg and the other a measurement leg wherein a portion of the measurement path is in a gas whose refractivity and/or effect on the optical path length of

15 the measurement path are to be measured.

As shown by blocks **506** and **508**, the previously generated light beam components are introduced into the interferometer legs so that each component has its phase shifted based on the optical path length it experiences in

20 traveling through the physical length of its assigned leg.

After the beams emerge from block **508**, they are combined in block **510** to generate a mixed optical signal. These mixed optical signals are then sent to block **512** where by means of photodetection corresponding electrical

25 signals, preferably heterodyne, are generated, and these electrical signals contain information about the relative phases between the light beam components. Preferably the electrical signals are heterodyne signals brought about by previously frequency shifting treatment.

30 In block **514**, the electrical signals may be directly analyzed to extract relative phase information which can then be passed on to blocks **516-520** or, superheterodyne

83

signals are generated, or modified heterodyne and then superheterodyne signals, or modified heterodyne signals, which are then subsequently analyzed for the relative phase information.

5 In block **516**, any phase ambiguities in homodyne, heterodyne, and/or superheterodyne signals are resolved, preferably by means and calculations previously elaborated in connection with describing the preferred embodiments.

 In block **518**, the refractivity of the gas and/or the
10 effect of the refractivity of the gas on the optical path length of the measurement path are calculated, corrections are applied as previously described, and output signals are generated for subsequent downstream applications or data format requirements.

15 Those skilled in the art may make other changes to the inventive apparatus and methods without departing from the scope of the inventive teachings. Therefore, it is intended that the embodiments shown and described be considered as illustrative and not in a limiting sense.

20 The interferometry systems described above can be especially useful in lithography applications (as, for example, represented at 267) used for fabricating large scale integrated circuits such as computer chips and the like. Lithography is the key technology driver for the
25 semiconductor manufacturing industry. Overlay improvement is one of the five most difficult challenges down to and below 100 nm line widths (design rules), see for example the *Semiconductor Industry Roadmap*, p82 (1997). Overlay depends directly on the performance, *i.e.* accuracy and
30 precision, of the distance measuring interferometers used to position the wafer and reticle (or mask) stages. Since a lithography tool may produce $50-100M/year of product, the economic value from improved performance distance

measuring interferometers is substantial. Each 1%
increase in yield of the lithography tool results in
approximately $1M/year economic benefit to the integrated
circuit manufacturer and substantial competitive advantage
5   to the lithography tool vendor.

The function of a lithography tool is to direct
spatially patterned radiation onto a photoresist-coated
wafer. The process involves determining which location of
the wafer is to receive the radiation (alignment) and
10 applying the radiation to the photoresist at that location
(exposure).

To properly position the wafer, the wafer includes
alignment marks on the wafer that can be measured by
dedicated sensors. The measured positions of the
15 alignment marks define the location of the wafer within
the tool. This information, along with a specification of
the desired patterning of the wafer surface, guides the
alignment of the wafer relative to the spatially patterned
radiation. Based on such information, a translatable
20 stage supporting the photoresist-coated wafer moves the
wafer such that the radiation will expose the correct
location of the wafer.

During exposure, a radiation source illuminates a
patterned reticle, which scatters the radiation to produce
25 the spatially patterned radiation. The reticle is also
referred to as a mask, and these terms are used
interchangeably below. In the case of reduction
lithography, a reduction lens collects the scattered
radiation and forms a reduced image of the reticle
30 pattern. Alternatively, in the case of proximity
printing, the scattered radiation propagates a small
distance (typically on the order of microns) before
contacting the wafer to produce a 1:1 image of the reticle

85

pattern. The radiation initiates photo-chemical processes in the photoresist that convert the radiation pattern into a latent image within the photoresist.

The interferometry systems described above are

5 important components of the positioning mechanisms that control the position of the wafer and reticle, and register the reticle image on the wafer.

In general, the lithography system, also referred to as an exposure system, typically includes an illumination

10 system and a wafer positioning system. The illumination system includes a radiation source for providing radiation such as ultraviolet, visible, x-ray, electron, or ion radiation, and a reticle or mask for imparting the pattern to the radiation, thereby generating the spatially

15 patterned radiation. In addition, for the case of reduction lithography, the illumination system can include a lens assembly for imaging the spatially patterned radiation onto the wafer. The imaged radiation exposes photoresist coated onto the wafer. The illumination

20 system also includes a mask stage for supporting the mask and a positioning system for adjusting the position of the mask stage relative to the radiation directed through the mask. The wafer positioning system includes a wafer stage for supporting the wafer and a positioning system for

25 adjusting the position of the wafer stage relative to the imaged radiation. Fabrication of integrated circuits can include multiple exposing steps. For a general reference on lithography, see, for example, J. R. Sheats and B. W. Smith, in _Microlithography: Science and Technology_ (Marcel

30 Dekker, Inc., New York, 1998), the contents of which are incorporated herein by reference.

The interferometry systems described above can be used to precisely measure the positions of each of the

wafer stage and mask stage relative to other components of the exposure system, such as the lens assembly, radiation source, or support structure. In such cases, the interferometry system can be attached to a stationary

5   structure and the measurement object attached to a movable element such as one of the mask and wafer stages. Alternatively, the situation can be reversed, with the interferometry system attached to a movable object and the measurement object attached to a stationary object.

10   More generally, the interferometry systems can be used to measure the position of any one component of the exposure system relative to any other component of the exposure system in which the interferometry system is attached, or supported by one of the components and the

15   measurement object is attached, or is supported by the other of the components.

An example of a lithography scanner 600 using an interferometry system 626 is shown in Fig. 6a. The interferometry system is used to precisely measure the

20   position of a wafer within an exposure system. Here, stage 622 is used to position the wafer relative to an exposure station. Scanner 600 comprises a frame 602, which carries other support structures and various components carried on those structures. An exposure base

25   604 has mounted on top of it a lens housing 606 atop of which is mounted a reticle or mask stage 616 used to support a reticle or mask. A positioning system for positioning the mask relative to the exposure station is indicated schematically by element 617. Positioning

30   system 617 can include, e.g., piezoelectric transducer elements and corresponding control electronics. Although, it is not included in this described embodiment, one or

87

more of the interferometry systems described above can
also be used to precisely measure the position of the mask
stage as well as other moveable elements whose position
must be accurately monitored in processes for fabricating
5   lithographic structures (see *supra* Sheats and Smith
Microlithography: Science and Technology).

Suspended below exposure base **604** is a support base
613 that carries wafer stage **622**. Stage **622** includes a
plane mirror for reflecting a measurement beam **654**
10   directed to the stage by interferometry system **626**. A
positioning system for positioning stage **622** relative to
interferometry system **626** is indicated schematically by
element **619**. Positioning system **619** can include, *e.g.*,
piezoelectric transducer elements and corresponding
15   control electronics. The measurement beam reflects back
to the interferometry system, which is mounted on exposure
base **604**. The interferometry system can be any of the
embodiments described previously.

During operation, a radiation beam **610**, *e.g.*, an
20   ultraviolet (UV) beam from a UV laser (not shown), passes
through a beam shaping optics assembly **612** and travels
downward after reflecting from mirror **614**. Thereafter,
the radiation beam passes through a mask (not shown)
carried by mask stage **616**. The mask (not shown) is imaged
25   onto a wafer (not shown) on wafer stage **622** via a lens
assembly **608** carried in a lens housing **606**. Base **604** and
the various components supported by it are isolated from
environmental vibrations by a damping system depicted by
spring **620**.

30   In other embodiments of the lithographic scanner, one
or more of the interferometry systems described previously
can be used to measure distance along multiple axes and

angles associated for example with, but not limited to,
the wafer and reticle (or mask) stages. Also, rather than
a UV laser beam, other beams can be used to expose the
wafer including, *e.g.*, x-ray beams, electron beams, ion
5   beams, and visible optical beams.

In addition, the lithographic scanner can include a
column reference in which interferometry system **626**
directs the reference beam to lens housing **606** or some
other structure that directs the radiation beam rather
10   than a reference path internal to the interferometry
system. The interference signal produce by interferometry
system **626** when combining measurement beam **654** reflected
from stage **622** and the reference beam reflected from lens
housing **606** indicates changes in the position of the stage
15   relative to the radiation beam. Furthermore, in other
embodiments the interferometry system **626** can be
positioned to measure changes in the position of reticle
(or mask) stage **616** or other movable components of the
scanner system. Finally, the interferometry systems can
20   be used in a similar fashion with lithography systems
involving steppers, in addition to, or rather than,
scanners.

As is well known in the art, lithography is a
critical part of manufacturing methods for making
25   semiconducting devices. For example, U.S. Patent
5,483,343 outlines steps for such manufacturing methods.
These steps are described below with reference to FIGS. **6b**
and **6c**. FIG. **6b** is a flow chart of the sequence of
manufacturing a semiconductor device such as a
30   semiconductor chip (*e.g.* IC or LSI), a liquid crystal
panel or a CCD. Step **651** is a design process for
designing the circuit of a semiconductor device. Step **652**

89

is a process for manufacturing a mask on the basis of the
circuit pattern design. Step **653** is a process for
manufacturing a wafer by using a material such as silicon.

5   Step **654** is a wafer process which is called a pre-
process wherein, by using the so prepared mask and wafer,
circuits are formed on the wafer through lithography.
Step **655** is an assembling step, which is called a post-
process wherein the wafer processed by step **654** is formed
into semiconductor chips. This step includes assembling

10   (dicing and bonding) and packaging (chip sealing). Step
656 is an inspection step wherein operability check,
durability check, and so on of the semiconductor devices
produced by step **655** are carried out. With these
processes, semiconductor devices are finished and they are

15   shipped (step **657**).

FIG. **6c** is a flow chart showing details of the wafer
process. Step **661** is an oxidation process for oxidizing
the surface of a wafer. Step **662** is a CVD process for
forming an insulating film on the wafer surface. Step **663**

20   is an electrode forming process for forming electrodes on
the wafer by vapor deposition. Step **664** is an ion
implanting process for implanting ions to the wafer. Step
665 is a photoresist process for applying a photoresist
(photosensitive material) to the wafer. Step **666** is an

25   exposure process for printing, by exposure, the circuit
pattern of the mask on the wafer through the exposure
apparatus described above. Step **667** is a developing
process for developing the exposed wafer. Step **668** is an
etching process for removing portions other than the

30   developed photoresist image. Step **669** is a photoresist
separation process for separating the photoresist material
remaining on the wafer after being subjected to the

etching process. By repeating these processes, circuit patterns are formed and superimposed on the wafer.

The interferometry systems described above can also be used in other applications in which the relative

5   position of an object needs to be measured precisely. For example, in applications in which a write beam such as a laser, x-ray, ion, or electron beam, marks a pattern onto a substrate as either the substrate or beam moves, the interferometry systems can be used to measure the relative

10 movement between the substrate and write beam.

As an example, a schematic of a beam writing system **700** is shown in FIG. 7. A source **710** generates a write beam **712**, and a beam focusing assembly **714** directs the radiation beam to a substrate **716** supported by a movable

15 stage **718**. To determine the relative position of the stage, an interferometry system **720** directs a reference beam **722** to a mirror **724** mounted on beam focusing assembly **714** and a measurement beam **726** to a mirror **728** mounted on stage **718**. Interferometry system **720** can be any of the

20 interferometry systems described previously. Changes in the position measured by the interferometry system correspond to changes in the relative position of write beam **712** on substrate **716**. Interferometry system **720** sends a measurement signal **732** to controller **730** that is

25 indicative of the relative position of write beam **712** on substrate **716**. Controller **730** sends an output signal **734** to a base **736** that supports and positions stage **718**. In addition, controller **730** sends a signal **738** to source **710** to vary the intensity of, or block, write beam **712** so that

30 the write beam contacts the substrate with an intensity sufficient to cause photophysical or photochemical change only at selected positions of the substrate. Furthermore,

91

in some embodiments, controller **730** can cause beam focusing assembly **714** to scan the write beam over a region of the substrate, *e.g.*, using signal **744**. As a result, controller **730** directs the other components of the system

5   to pattern the substrate. The patterning is typically based on an electronic design pattern stored in the controller. In some applications the write beam patterns a photoresist coated on the susbstrate and in other applications the write beam directly patterns, *e.g.*,

10   etches, the substrate.

An important application of such a system is the fabrication of masks and reticles used in the lithography methods described previously. For example, to fabricate a lithography mask an electron beam can be used to pattern a

15   chromium-coated glass substrate. In such cases where the write beam is an electron beam, the beam writing system encloses the electron beam path in a vacuum. Also, in cases where the write beam is, *e.g.*, an electron or ion beam, the beam focusing assembly includes electric field

20   generators such as quadrapole lenses for focusing and directing the charged particles onto the substrate under vacuum. In other cases where the write beam is a radiation beam, *e.g.*, x-ray, UV, or visible radiation, the beam focusing assembly includes corresponding optics for

25   focusing and directing the radiation to the substrate.

Yet other changes may be made to the invention. For example, it may be desirable in certain applications to monitor the refractive index of the gas contained on both the reference and in the measurement legs of the

30   interferometer. Examples include the well-known column reference style of interferometer, in which the reference leg comprises a target optic placed at one position within a mechanical system, and the measurement leg comprises a

92

target optic placed at a different position within the same mechanical system. Another example application relates to the measurement of small angles, for which both the measurement and reference beams impinge upon the same

5 target optic but at a small physical offset, thereby providing a sensitive measure of the angular orientation of the target optic. These applications and configurations are well known to those skilled in the art and the necessary modifications are intended to be within

10 the scope of the invention.

Additional alternative means of achieving substantial insensitivity to Doppler shifting in a heterodyne interferometer is to track the Doppler shift and compensate by either (1) adjusting the frequency

15 difference between the reference and measurement beams, (2) adjusting the clock frequency of one or both of the electronic A/D modules or (3) any similar means of continuously matching the apparent heterodyne beat frequency of the two wavelengths by active adjustment of

20 the drive or detection electronics.

It is understood that while the invention has been described in conjunction with the detailed description thereof, the foregoing description is intended to illustrate and not limit the scope of the invention, which

25 is defined by the scope of the appended claims.

What is claimed is:

1.   1.   Interferometric apparatus for measuring the
2. effects of the refractive index of a gas in a measurement
3. path, said interferometric apparatus comprising:
4.   interferometer means comprising first and second
5. measurement legs, said first and second measurement legs
6. having optical paths structured and arranged such that at
7. least one of them has a variable physical length and at
8. least one of them is at least in part occupied by the
9. gas, the optical path length difference between said
10. first and second measurement legs varying in accordance
11. with the difference between the respective physical
12. lengths of their optical paths and the properties of said
13. gas;
14.   means for generating at least two light beams having
15. different wavelengths;
16.   means for introducing first and second predetermined
17. portions of each of said light beams into said first and
18. second measurement legs, respectively, of said
19. interferometer means so that each of at least one of said
20. first and second predetermined portions of said light
21. beams travels through said first and second measurement
22. legs along predetermined optical paths with the same
23. number of passes, said predetermined first and second
24. portions of said light beams emerging from said
25. interferometer means as exit beams containing information
26. about the respective optical path lengths through said
27. first and second measurement legs at said wavelengths;
28.   means for combining said exit beams to produce mixed
29. optical signals containing information corresponding to
30. the phase differences between each of said exit beams
31. from corresponding ones of said predetermined optical

94

32   paths of said first and second measurement legs at said
33   wavelengths;
34   means for detecting said mixed optical signals and
35   generating electrical interference signals containing
36   information corresponding to the effects of the index of
37   refraction of the gas at said different beam wavelengths
38   and the difference in physical path lengths of said
39   measurement legs and their relative rate of change; and
40   electronic means for analyzing said electrical
41   interference signals to determine the effects of said gas
42   in said measurement leg(s) while compensating for the
43   relative rates at which the physical path lengths of said
44   first and second measurement legs are changing.

1   2.   The interferometric apparatus of claim 1 wherein
2   said electronic means comprises means for directly
3   receiving said electrical interference signals and
4   detecting phases therefrom to generate phase signals
5   where said phase signals contain information
6   corresponding to the effects of the index of refraction
7   of the gas at said different beam wavelengths and the
8   difference in physical path lengths of said measurement
9   legs and their rates of change.

1   3.   The interferometric apparatus of claim 2 wherein
2   said electronic means further comprises means for
3   resolving phase redundancy in said phase signals.

1   4.   The interferometric apparatus of claim 1 wherein
2   said different wavelengths have an approximate harmonic
3   relationship to each other, said approximate harmonic
4   relationship being expressed as a sequence of ratios, each

95

5   ratio being comprised of a ratio of low order, non-zero
6   integers.

1   5. The interferometric apparatus of claim 1 wherein
2   said electronic means further includes phase analyzing
3   means for receiving said electrical interference signals
4   and generating initial electrical phase signals
5   containing information corresponding to the effects of
6   the index of refraction of the gas at said different beam
7   wavelengths and the physical path lengths of said
8   measurement legs occupied by said gas and their rates of
9   change.

1   6. The interferometric apparatus of claim 5 wherein
2   said electronic means further includes multiplying means
3   for multiplying said initial phase signals by factors
4   proportional to said wavelengths to generate modified
5   phase signals.

1   7. The interferometric apparatus of claim 6 wherein
2   said electronic means further includes means for
3   receiving said modified phase signals and selectively
4   adding and subtracting them to generate sum and
5   difference phase signals containing information
6   corresponding to the effects of the index of refraction
7   of the gas at said different beam wavelengths and the
8   difference in physical path lengths of said measurement
9   legs o and their relative rates of change.

1   8. The interferometric apparatus of claim 7 wherein
2   said electronic means further includes means for receiving
3   said sum and difference phase signals and at least one of

4   said initial phase signals to determine the difference in

5   physical lengths, L, of said measurement legs.

1   9.   The interferometric apparatus of claim 8 further

2   including means for resolving redundancies among said

3   initial phase and said sum and difference phase signals.

1   10.   The interferometric apparatus of claim 6

2   wherein said wavelengths are non-harmonically related.

1   11.   The interferometric apparatus of claim 6 wherein

2   said wavelengths of said light beams have an approximate

3   harmonic relationship to each other, said approximate

4   harmonic relationship being expressed as a sequence of

5   ratios, each ratio being comprised of a ratio of low order

6   non-zero integers.

1   12.   The interferometric apparatus of claim 1

2   further including a microlithographic means operatively

3   associated with said interferometric apparatus for

4   fabricating integrated circuits on wafers, said

5   microlithographic means comprising:

6   at least one stage;

7   an illumination system for imaging spatially

8   patterned radiation onto the wafer; and

9   at least one positioning system for adjusting the

10 position of said at least one stage;

11   wherein said interferometric apparatus is adapted to

12 measure the position of said at least one stage.

1   13.   The interferometric apparatus of claim 1 further

2   including a microlithographic means operatively associated

3   with said interferometric apparatus for use in fabricating

4   integrated circuits on a wafer, said microlithographic

5   means comprising:

6   at least one stage for supporting a wafer;

7   an illumination system including a radiation source,

8   a mask, a positioning system, a lens assembly, and

9   predetermined portions of said interferometric apparatus,

10   said microlithographic means being operative such

11 that the source directs radiation through said mask to

12 produce spatially patterned radiation, said positioning

13 system adjusts the position of said mask relative to

14 radiation from said source, said lens assembly images said

15 spatially patterned radiation onto the wafer, and said

16 interferometric apparatus measures the position of said

17 mask relative to said radiation from said source.

1   14. The interferometric apparatus of claim 1

2   further including microlithographic apparatus operatively

3   associated with said interferometric apparatus for

4   fabricating integrated circuits comprising first and

5   second components, said first and second components being

6   moveable relative to one another, said first first and

7   second components being connected with said first and

8   second measurement legs, moving in concert therewith,

9   such that said interferometric apparatus measures the

10 position of said first component relative to said second

11 component.

1   15. The interferometric apparatus of claim 1 further

2   including a beam writing system operatively associated

3   with said interferometric apparatus for use in fabricating

4   a lithography mask, said beam writing system comprising:

5   a source for providing a write beam to pattern a

6   substrate;

98

7   at least one stage for supporting a substrate;

8   a beam directing assembly for delivering said write

9   beam to the substrate; and

10   a positioning system for positioning said at least

11 one stage and said beam directing assembly relative to one

12 another,

13   said interferometric apparatus being adapted to

14 measure the position of said at least one stage relative

15 to said beam directing assembly.

1   16.   The interferometric apparatus of claim 11

2   wherein the relative precision of said approximate

3   harmonic relationship expressed as said sequence of

4   ratios is an order of magnitude or more less than the

5   dispersion of the refractive index of said gas times the

6   relative precision, ε, required for the measurement of

7   the refractivity of said gas or of the change in the

8   difference in optical path lengths of said measurement

9   legs.

1   17.   The interferometric apparatus of claim 1

2   wherein the relative precision of the relationship

3   between said wavelengths expressed as a ratio(s) relative

4   to a known ratio is greater than a predetermined value

5   corresponding to the precision requirements of a

6   downstream application.

1   18.   The interferometric apparatus of claim 17

2   further including means for monitoring the relative

3   precision of said relationship expressed as said ratio.

1   19.   The interferometric apparatus of claim 18

2   further including means responsive to said means for

99

3 monitoring said relative precision of said relationship

4 expressed as said ratio for providing a feedback signal to

5 control said means for generating said light beams so that

6 said relative precision of said relationship expressed as

7 said ratio is substantially equal to or less than the

8 predetermined value corresponding to the precision

9 requirements of a downstream application.

1   20.   The interferometric apparatus of claim 1 wherein

2 said at least two light beams each have orthogonal

3 polarization states.

1   21.   The interferometric apparatus of claim 20

2 further including means for introducing a frequency

3 difference(s) between said orthogonal polarization states

4 of said light beams.

1   22.   The interferometric apparatus of claim 21

2 wherein said means for detecting said mixed optical

3 signals comprises a single photodetector for receiving

4 selected ones of said mixed optical signals beams having

5 predetermined frequency differences.

1   23.   The interferometric apparatus of claim 21

2 wherein said means for combining said exit beams are

3 adapted to mix said polarization states of said light

4 beams.

1   24.   The interferometric apparatus of claim 23

2 wherein said information corresponding to said phase

3 differences in said mixed optical signals are

4   phase shifts φ_j related to the differences in total round-

5   trip physical lengths pL of said measurement legs

6   occupied by said gas according to the formulae

7

8   $$\varphi_j = Lpk_j n_j + \zeta_j \quad , \quad j = 1, 2, \ldots$$

9   where

10 $$k_j = 2\pi/\lambda_j \quad ,$$

11 p is the number of multiple passes through the at least

12 one of said first and second measurement legs, and n_j are

13 the refractive indices of gas in said at least one of said

14 measurement legs occupied by the gas corresponding to

15 wavelength, λ_j, and ζ_j are phase offsets not associated

16 with optical paths.

1   25.   The interferometric apparatus of claim 24

2   wherein said electrical interference signals comprise

3   heterodyne signals of the form:

4

5   $$s_j = A_j \cos\left[\alpha_j(t)\right] \quad , \quad j = 1, 2, \ldots$$

6   where the time-dependent arguments $\alpha_j(t)$ are given by

7

8   $$\alpha_j(t) = 2\pi f_j t + \varphi_j \quad , \quad j = 1, 2, \ldots .$$

9   26.   The interferometric apparatus of claim 25

10 wherein said different wavelengths have an approximate

11 harmonic relationship to each other, said approximate

12 harmonic relationship being expressed as a sequence of

13 ratios, each ratio being comprised of a ratio of low

14 order, non-zero integers.

1   27.   The interferometric apparatus of claim 1 wherein

2 said different wavelengths have a relationship to each

3 other expressed as a ratio, said ratio being non-harmonic.

1   28.   The interferometric apparatus of claim 25

2 wherein said electronic means is adapted to receive said

3 heterodyne signals and determine said phase shifts,

4 $$\varphi_j = Lpk_j n_j + \zeta_j \quad , \quad j = 1, 2, \ldots .$$

1   29.   The interferometric apparatus of claim 26

2 further including means for generating at least two

3 modified heterodyne signals from said heterodyne signals,

4 said modified heterodyne signals being of the form:

5

6 $$\widetilde{s}_j = \widetilde{A}_j \cos\left[p_j \alpha_j(t)\right] \quad , \quad j = 1, 2, \ldots ,$$

7 where:

8 $$\alpha_j(t) = 2\pi f_j t + \varphi_j \quad , \quad j = 1, 2, \ldots .$$

9 where p_j are non-zero integers where $p_1 \neq p_2$ and have the

10 same ratio as that of said approximate harmonic

11 relationship of said wavelengths.

1   30.   The interferometric apparatus of claim 29

2 further including means for generating a superheterodyne

3 signal of the form:

4

5 $$S = \widetilde{s}_1 \widetilde{s}_2$$

6 where said superheterodyne signal S is comprised of two

7 sidebands with a suppressed carrier expressed as:

8 $$S = S^+ + S^- \quad \text{where}$$

9 $$S^+ = \frac{1}{2}\widetilde{A}_1\widetilde{A}_2 \cos(2\pi v t + \vartheta) \quad ,$$

102

10
$$S^{-} = \frac{1}{2}\tilde{A}_{1}\tilde{A}_{2}\cos(2\pi Ft + \Phi) \qquad ,$$

11
$$\nu = (p_{1}f_{1} + p_{2}f_{2})$$

12
$$\vartheta = (p_{1}\varphi_{1} + p_{2}\varphi_{2})$$

13
$$F = (p_{1}f_{1} - p_{2}f_{2})$$

14
$$\Phi = (p_{1}\varphi_{1} - p_{2}\varphi_{2}) \qquad ,$$

15　whereby said superheterodyne signal S is comprised of two

16　sidebands, S^{+} and S^{-}, of equal amplitude, one sideband

17　with frequency ν and phase ϑ and a second sideband with

18　frequency F and phase Φ.

1　　　　31.　The interferometric apparatus of claim 26

2　further including means for generating at least two

3　modified heterodyne signals from said heterodyne signals,

4　said modified heterodyne signals being of the form:

5

6
$$\tilde{s}_{1}' = \tilde{A}_{1}'\cos[\alpha_{1}(t)/p_{2}] \qquad ,$$
$$\tilde{s}_{2}' = \tilde{A}_{2}'\cos[\alpha_{2}(t)/p_{1}]$$

7　where

8
$$\alpha_{j}(t) = 2\pi f_{j}t + \varphi_{j} \qquad , \qquad j = 1, 2, \ldots$$

9　and p_{1} and p_{2} are non-zero integers with $p_{1} \neq p_{2}$ and have

10　the same ratio as that of said approximate harmonic

11　relationship of said wavelengths.

1　　　　32.　The interferometric apparatus of claim 1 wherein

2　said electronic means is further adapted to determine the

3　difference in physical lengths, pL, of said measurement

4　legs occupied by said gas.

1　　　　33.　The apparatus of claim 32 wherein said

2　electronic means is configured to receive the intrinsic

103

3 optical property, the reciprocal dispersive power, Γ, of

4 the gas to calculate the difference in physical lengths,

5 L, as:

6 $$\Gamma = \frac{[n_1(\lambda_1)-1]}{[n_3(\lambda_3)-n_2(\lambda_2)]}, \quad \text{and}$$

7 λ_1, λ_2, and λ_3 are wavelengths and n_1, n_2, and n_3 are indices of

8 refraction and wherein the denominator may be replaced by

9 $$[n_3(\lambda_3)-n_1(\lambda_1)] \text{ or } [n_2(\lambda_2)-n_1(\lambda_1)].$$

1   34. The interferometric apparatus of claim 1 further

2 including a microlithographic means operatively associated

3 with said interferometer means such that said difference

4 in physical lengths, L, may be used to determine the

5 change in relative distance between predetermined elements

6 of said microlithographic means.

1   35. The interferometric apparatus of claim 1 further

2 including means for aligning said light beams into a

3 single substantially collinear light beam that travels

4 along said at least one of said measurement paths occupied

5 by gas.

1   36. The interferometric apparatus of claim 1 wherein

2 said interferometer means comprises a polarized Michelson

3 interferometer.

1   37. The interferometric apparatus of claim 1 wherein

2 said interferometer means comprises a differential plane

3 mirror interferometer.

1   38. The interferometer apparatus of claim 1 further

2 including means for directly receiving said electrical

3 interference signals from said means for detecting and

4 converting said electrical interference signals to
5 digital form to reduce phase errors in further downstream
6 calculations.

1   39.   Interferometric method for measuring the
2 effects of the refractive index of a gas in a measurement
3 path, said interferometric apparatus comprising:
4   providing an interferometer means comprising a first
5 and second measurement legs, said first and second
6 measurement legs having optical paths structured and
7 arranged such that at least one of them has a variable
8 physical length and at least one of them is at least in
9 part occupied by gas, the optical path length difference
10 between said first and second measurement legs varying in
11 accordance with the difference in the respective physical
12 lengths of their optical paths and the properties of said
13 gas;
14   generating at least two light beams having different
15 wavelengths;
16   introducing first and second predetermined portions
17 of each of said light beams into said first and second
18 measurement legs, respectively, of said interferometer
19 means so that each of at least one of said first and
20 second predetermined portions of said light beams travels
21 through said first and second measurement legs along
22 predetermined optical paths with the same number of
23 passes, said predetermined first and second portions of
24 said light beams emerging from said interferometer means
25 as exit beams containing information about the respective
26 optical path lengths through said first and second
27 measurement legs at said wavelengths;
28   combining said exit beams to produce mixed optical
29 signals containing information corresponding to the phase

105

30 differences between each of said exit beams from
31 corresponding ones of said predetermined optical paths of
32 said first and second measurement legs at said
33 wavelengths;
34   detecting said mixed optical signals and generating
35 electrical interference signals containing information
36 corresponding to the effects of the index of refraction
37 of the gas at said different beam wavelengths and the
38 relative physical path lengths between said first and
39 second measurement legs and their relative rates of
40 change; and
41   electronically analyzing said interference
42 electrical signals to determine the effects of said gas
43 in said measurement leg(s) while compensating for the
44 relative rates at which the physical path lengths of said
45 first and second measurement legs are changing.

1   40. The interferometric method of claim 39 wherein
2 said different wavelengths have an approximate harmonic
3 relationship to each other, said approximate harmonic
4 relationship being expressed as a sequence of ratios,
5 each ratio being comprised of a ratio of low order, non-
6 zero integers.

1   41. The interferometric method of claim 40 wherein
2 the relative precision of said approximate harmonic
3 relationship expressed as said sequence of ratios is an
4 order of magnitude or more less than the dispersion of
5 the refractive index of said gas times the relative
6 precision required for the measurement of the
7 refractivity of said gas or of the change in the
8 differene in optical path lengths of said measurement
9 legs due to said gas.

106

1   42.   The interferometric method of claim 40 further
2 including the step of monitoring the relative precision of
3 said approximate harmonic relationship expressed as said
4 sequence of ratios.

1   43.   The interferometric method of claim 42 further
2 including the step, responsive to the step of monitoring
3 said relative precision of said approximate harmonic
4 relationship, of providing a feedback signal to control
5 said light beams so that said relative precision of said
6 approximate harmonic relationship is within an order of
7 magnitude or more less than the dispersion of the
8 refractive index of said gas times the relative precision
9 required for the measurement of the refractivity of said
10 gas or of the change in the difference in optical path
11 lengths of said measurement legs due to said gas.

1   44.   The interferometric method of claim 39 wherein
2 said at least two light beams each have orthogonal .
3 polarization states.

1   45.   The interferometric method of claim 44 further
2 including the step of introducing a frequency
3 difference(s) between said orthogonal polarization states
4 of said light beams.

1   46.   The interferometric method of claim 45 wherein
2 said step of combining said exit beams comprises mixing
3 said polarization states of said light beams.

1   47.   The interferometric method of claim 46 wherein
2 said information corresponding to said phase differences
3 in said mixed optical signals are phase shifts φ_j related

4 to the differences in total round-trip physical lengths

5 pL of said measurement legs occupied by said gas

6 according to the formulae

7

8 $$\varphi_j = Lpk_jn_j + \zeta_j \quad , \quad j = 1, 2, \ldots$$

9 where

10 $$k_j = 2\pi/\lambda_j \quad ,$$

11 p is the number of multiple passes through at least one

12 of said first and second measurement legs, and n_j are the

13 refractive indices of gas in said at least one measurement

14 leg corresponding to wavelength, λ_j.

1   48. The interferometric method of claim 47 wherein

2 said electrical interference signals comprise heterodyne

3 signals of the form:

4

5 $$s_j = A_j \cos\left[\alpha_j(t)\right] \quad , \quad j = 1, 2, \ldots$$

6 where the time-dependent arguments $\alpha_j(t)$ are given by

7

8 $$\alpha_j(t) = 2\pi f_j t + \varphi_j \quad , \quad j = 1, 2, \ldots \; .$$

9   49. The interferometric method of claim 48 wherein

10 said step of electronically analyzing comprises receiving

11 said heterodyne signals and determining said phase shifts,

12 $$\varphi_j = Lpk_jn_j + \zeta_j \quad , \quad j = 1, 2, \ldots$$

1   50. The interferometric method of claim 48 wherein

2 said wavelengths are harmonically related and further

3 including the step of generating at least two modified

4 heterodyne signals from said heterodyne signals, said

5 modified heterodyne signals being of the form:

6

7
$$\widetilde{s}_j = \widetilde{A}_j \cos\left[p_j \alpha_j(t)\right] \quad , \quad j = 1, 2, \ldots$$

8 where:

9
$$\alpha_j(t) = 2\pi f_j t + \varphi_j \quad , \quad j = 1, 2, \ldots$$

10 and p_1 and p_2 are non-zero integers with $p_1 \neq p_2$ and have

11 the same ratio as that of said approximate harmonic

12 relationship of said wavelengths.

1   51. The interferometric method of claim 50 further

2 including the step of generating a superheterodyne signal

3 of the form:

4

5
$$S = \widetilde{s}_1 \widetilde{s}_2$$

6 where said superheterodyne signal S is comprised of two

7 sidebands with a suppressed carrier expressed as:

8
$$S = S^+ + S^- \quad \text{where}$$

9
$$S^+ = \frac{1}{2}\widetilde{A}_1\widetilde{A}_2\cos(2\pi\nu t + \vartheta) \quad ,$$

10
$$S^- = \frac{1}{2}\widetilde{A}_1\widetilde{A}_2\cos(2\pi F t + \Phi) \quad ,$$

11
$$\nu = \left(p_1 f_1 + p_2 f_2\right)$$

12
$$\vartheta = \left(p_1\varphi_1 + p_2\varphi_2\right)$$

13
$$F = \left(p_1 f_1 - p_2 f_2\right)$$

14
$$\Phi = \left(p_1\varphi_1 - p_2\varphi_2\right) \quad ,$$

15 whereby said superheterodyne signal S is comprised of two

16 sidebands, S^+ and S^-, of equal amplitude, one sideband

17 with frequency ν and phase ϑ and a second sideband with

18 frequency F and phase Φ.

1   52. The interferometric method of claim 48 further

2 including the step of generating at least two modified

109

3 heterodyne signals from said heterodyne signals, said
4 modified heterodyne signals being of the form:
5

$$\tilde{s}_1' = \tilde{A}_1' \cos\left[\alpha_1(t)/p_2\right] \quad ,$$
$$\tilde{s}_2' = \tilde{A}_2' \cos\left[\alpha_2(t)/p_1\right]$$

6

7 where

8

$$\alpha_j(t) = 2\pi f_j t + \varphi_j \quad , \qquad j = 1, 2, \ldots$$

9 and p_1 and p_2 are non-zero integers with $p_1 \neq p_2$ and have
10 the same ratio as that of said approximate harmonic
11 relationship of said wavelengths.

1   53.   The interferometric method of claim 39 wherein
2 said step of electronically analyzing comprises
3 determining the difference in physical lengths, L, of
4 said measurement legs.

1   54.   The interferometric method of claim 53 wherein
2 said difference in physical lengths, L, may be used to
3 determine the relative distance between predetermined
4 elements of a microlithographic means.

1   55.   The interferometric method of claim 53 wherein
2 said difference in physical lengths, L, is calculated
3 with a predetermined value for the reciprocal relative
4 dispersion, Γ, of said gas where:

5

$$\Gamma = \frac{[n_1(\lambda_1) - 1]}{[n_3(\lambda_3) - n_2(\lambda_2)]} , \quad \text{and}$$

6 $\lambda_1, \lambda_2,$ and λ_3 are wavelengths and $n_1, n_2,$ and n_3 are indices of
7 refraction and wherein the denominator may be replaced by
8 $[n_3(\lambda_3) - n_1(\lambda_1)]$ or $[n_2(\lambda_2) - n_1(\lambda_1)]$.

1   56. The interferometric method of claim 39 further
2   including the step of aligning said light beams into a
3   single substantially collinear light beam that travels
4   along at least one of said measurement legs.

1   57. The interferometric method of claim 39 wherein
2   said interferometer means comprises a polarized Michelson
3   interferometer.

1   58. The interferometric method of claim 39 wherein
2   said interferometer means comprises a differential plane
3   mirror interferometer.

1   59. The interferometer method of claim 39 further
2   including the step of directly receiving said electrical
3   interference signals after their formation to transform
4   them to digital form to reduce phase errors in further
5   downstream calculations.

1   60. The interferometric method of claim 39 further
2   including the following steps for forming integrated
3   circuits on a wafer:
4   providing at least one moveable stage;
5   imaging spatially patterned radiation onto a wafer;
6   adjusting the position of said at least one stage;
7   and
8   measuring the position of said at least one stage.

1   61. The interferometric method of claim 39 further
2   including the steps of:
3   supporting a wafer on at least one moveable stage;
4   directing a source of radiation through a mask and lens
5   assembly to produce spatially patterned radiation,

111

6   adjusting the position of said mask relative to
7 radiation from said source, said lens assembly imaging
8 said spatially patterned radiation onto the wafer, and
9 measuring the position of said mask relative to said
10 radiation from said source.

1   62. The interferometric method of claim 39 further
2 including the step of providing a microlithographic
3 apparatus for fabricating integrated circuits comprising
4 first and second components, said first and second
5 components being moveable relative to one another, said
6 first and second components being connected with said
7 first and second measurement legs, respectively, moving in
8 concert therewith, such that the position of said first
9 component relative to said second component is measured.

1   63. The interferometric method of claim 39 further
2 including the steps of:
3   providing a pattern of radiation with a write beam
4 source;
5   supporting a substrate on at least one stage;
6   directing said write beam such that said pattern of
7 radiation impinges onto the substrate; and
8   positioning said at least one stage and said write
9 beam of radiation relative to one another, and
10   measuring the position of said at least one stage
11 relative to said write beam.

1   64. The interferometric method of claim 39 wherein
2 said wavelengths have a non-harmonic relationship with
3 respect to one another.

112

1   65. The interferometric method of claim 39 wherein
2   said step of electronically analyzing further includes the
3   step of receiving said electrical interference signals and
4   extracting the phase therefrom to generate initial
5   electrical phase signals containing information
6   corresponding to the effects of the index of refraction of
7   the gas at said different beam wavelengths and the
8   differnce in physical path lengths of said measurement
9   legs and their relative rates of change.

1   66. The interferometric method of claim 65 wherein
2   said step of electronically analyzing further includes the
3   step of multiplying said initial phase signals by factors
4   proportional to said wavelengths to generate modified
5   phase signals.

1   67. The interferometric method of claim 66 wherein
2   said step of electronically analyzing further includes the
3   step of receiving said modified phase signals and
4   selectively adding and subtracting them to generate sum
5   and difference phase signals containing information
6   corresponding to the effects of the index of refraction of
7   the gas at said different beam wavelengths and the
8   differences in round trip physical lengths of said
9   measurement legs and their relative rates of change.

1   68. The interferometric method of claim 67 wherein
2   said step of electronically analyzing further includes the
3   step of receiving said sum and difference phase signals
4   and at least one of said initial phase signals to
5   determine the difference in round trip physical lengths,
6   L, of said measurement legs.

113

1   69. The interferometric method of claim 67 further
2 including the step of resolving redundancies among said
3 initial phase and said sum and difference phase signals.

1   70. The interferometric method of claim 66 wherein
2 said wavelengths are non-harmonically related.

1   71. The interferometric method of claim 66 wherein
2 said wavelengths of said light beams have an approximate
3 harmonic relationship to each other, said approximate
4 harmonic relationship being expressed as a sequence of
5 ratios, each ratio being comprised of a ratio of low order
6 non-zero integers.

1   72. The interferometric method of claim 46 wherein
2 the step of introducing frequency differences between said
3 orthogonal polarization states of said light beams is such
4 that at least two of said light beams have different
5 frequencies between their respective polarization states
6 and so that a single photodetector can be used for
7 generating phase signals from at least two of said exit
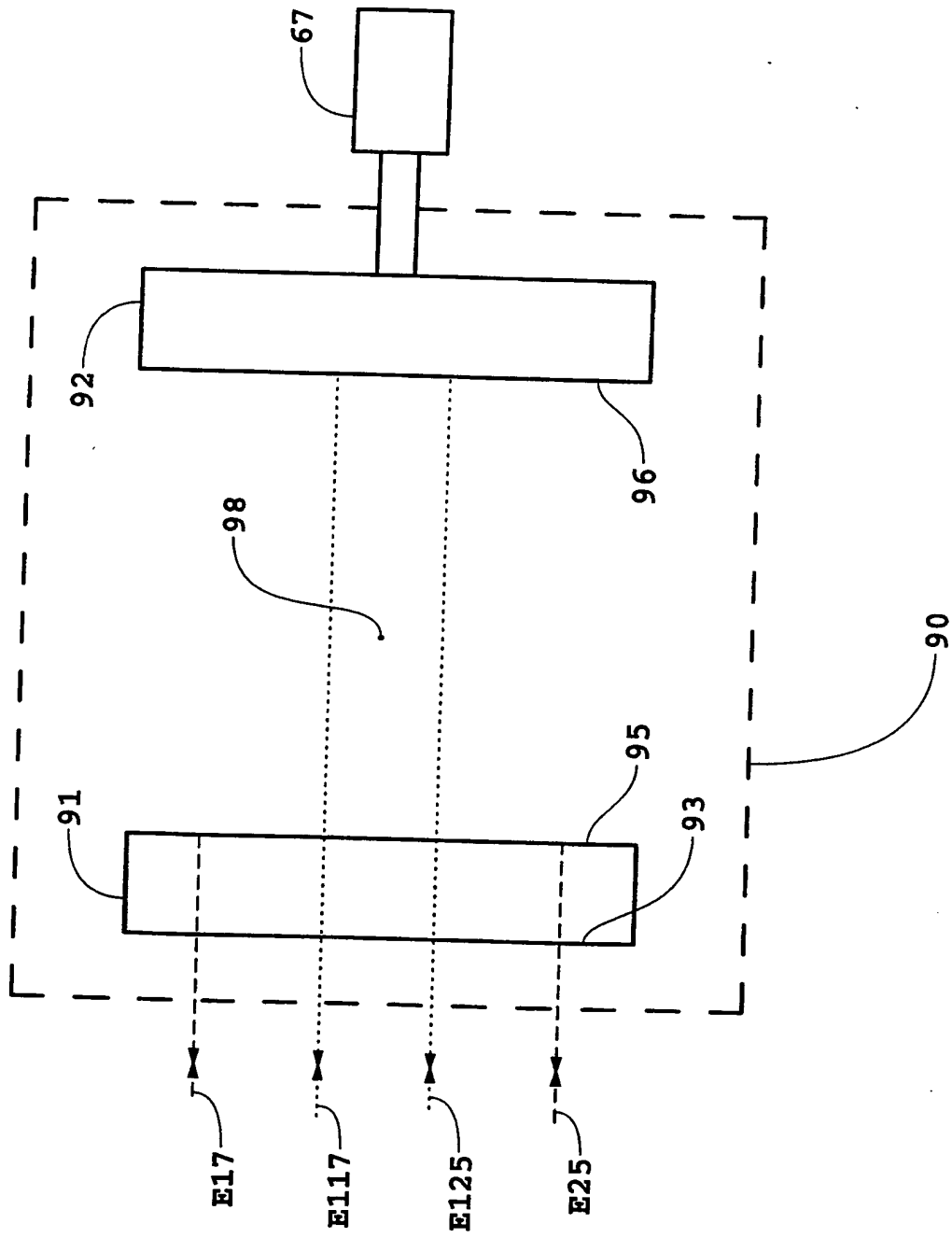8 beams.
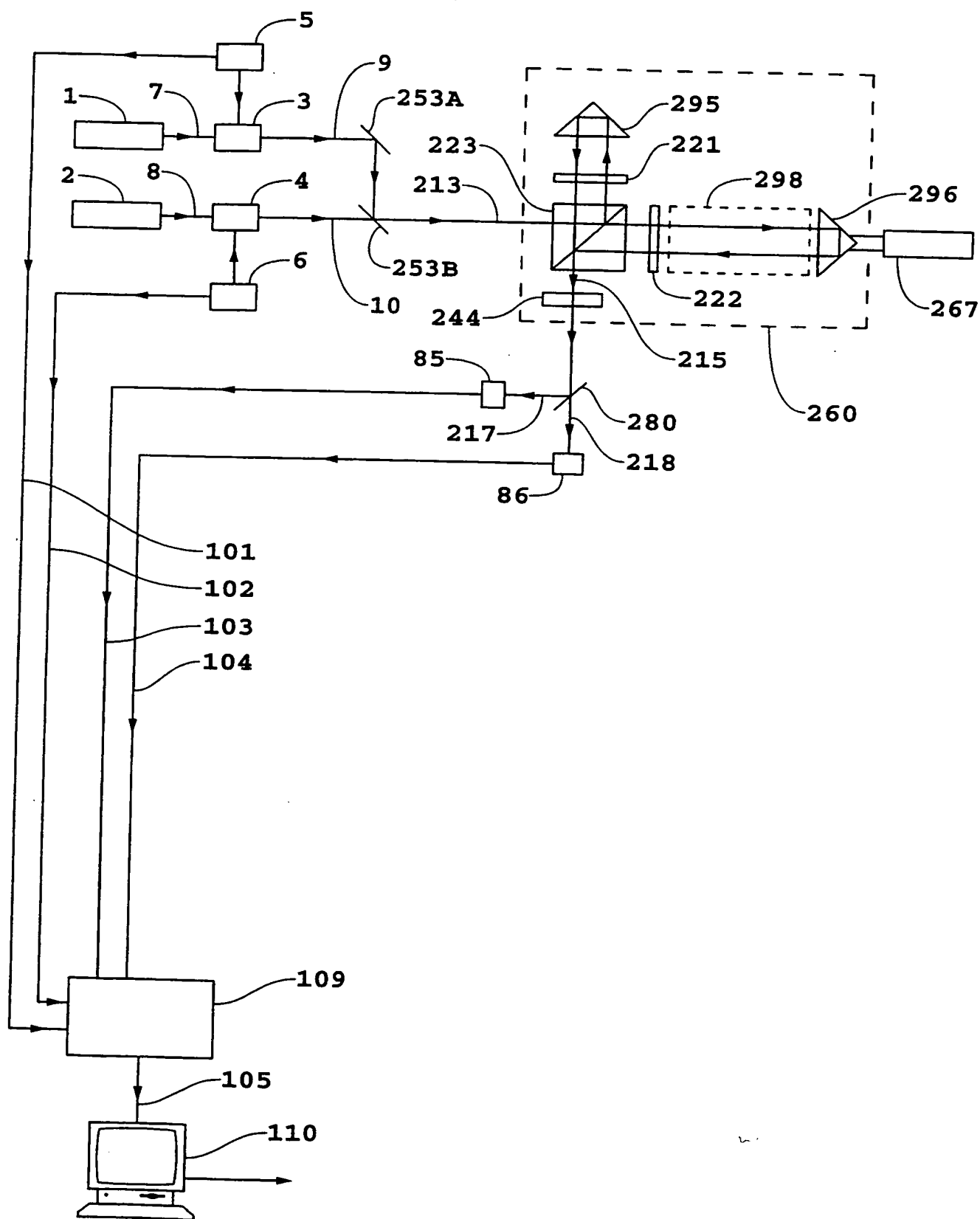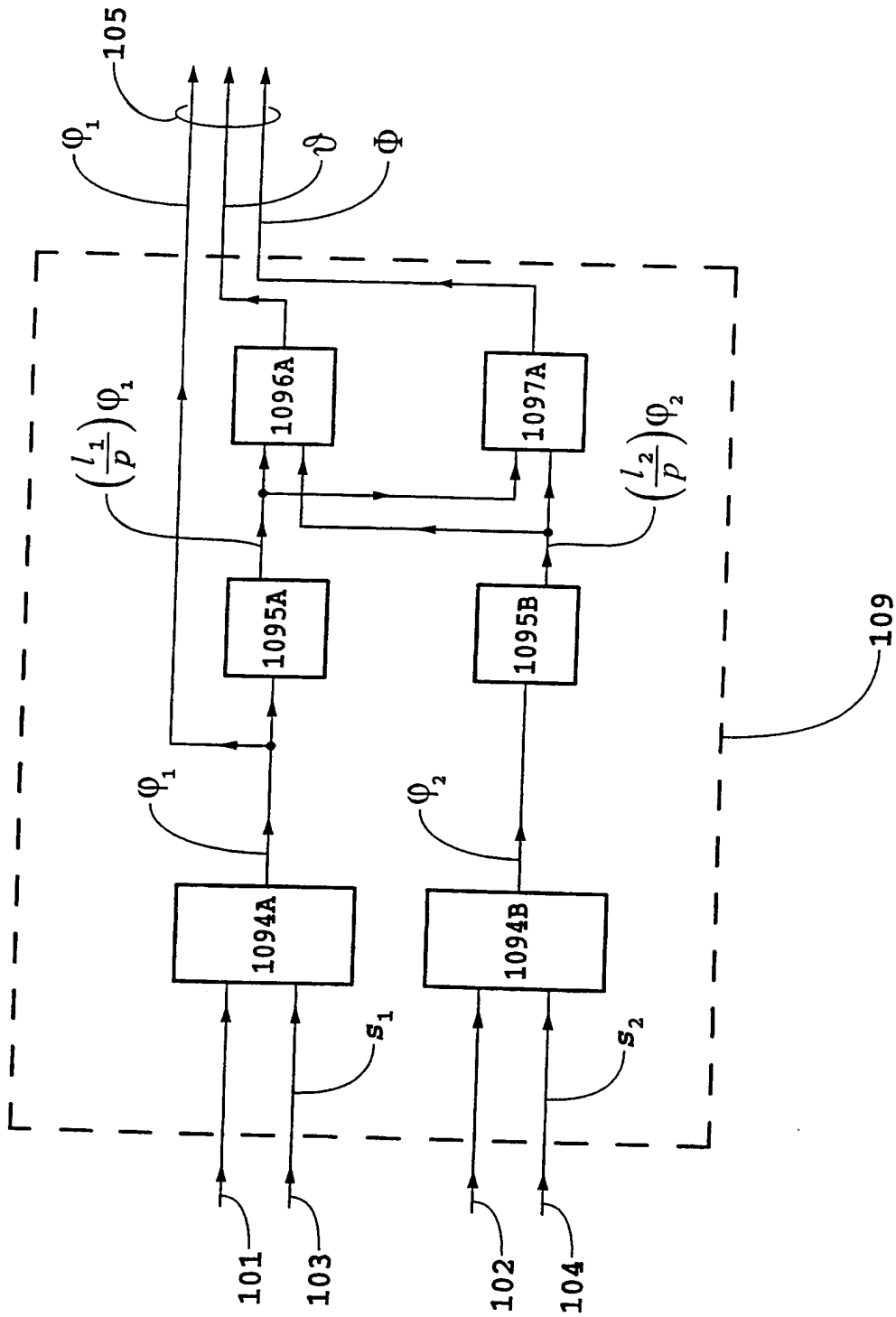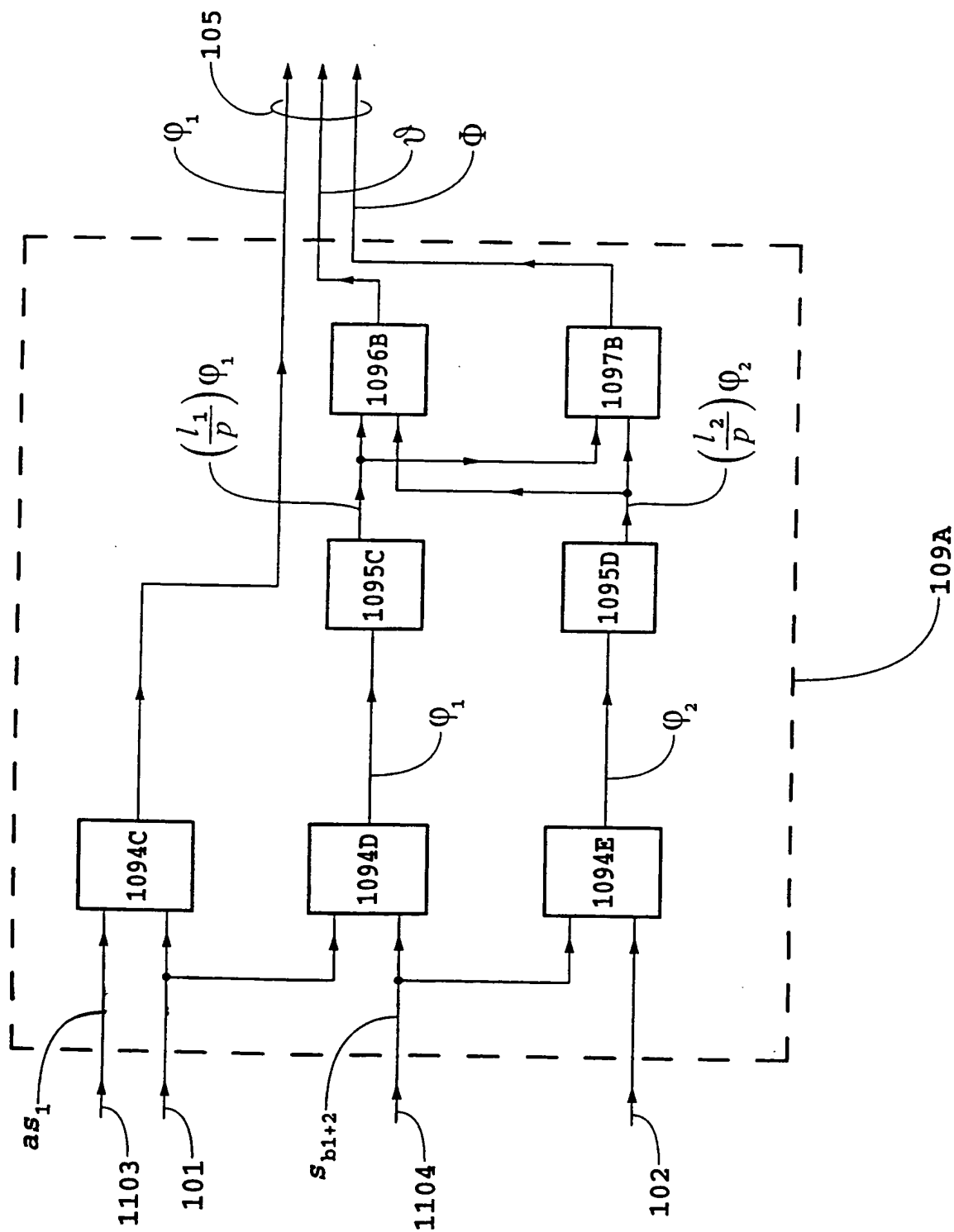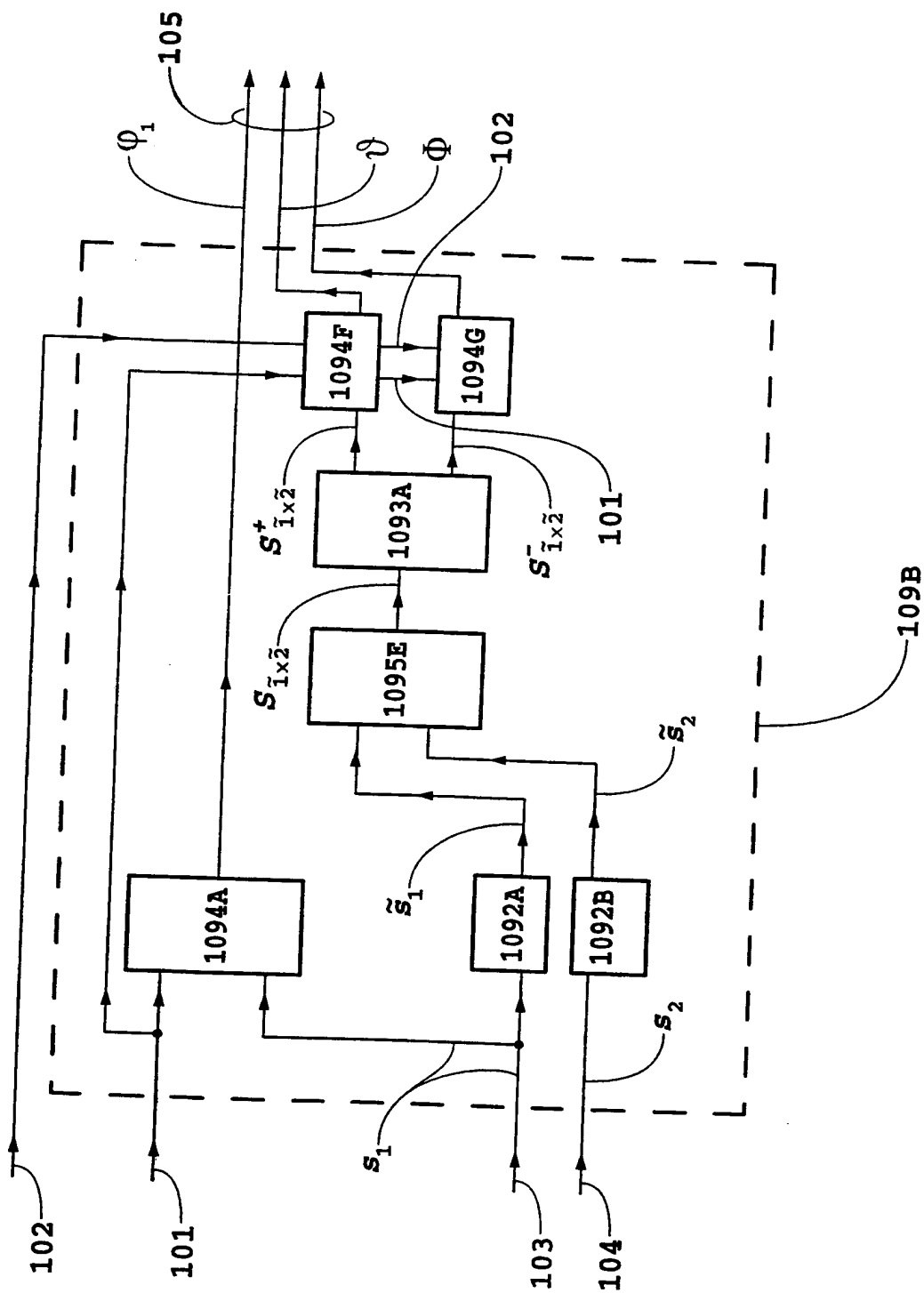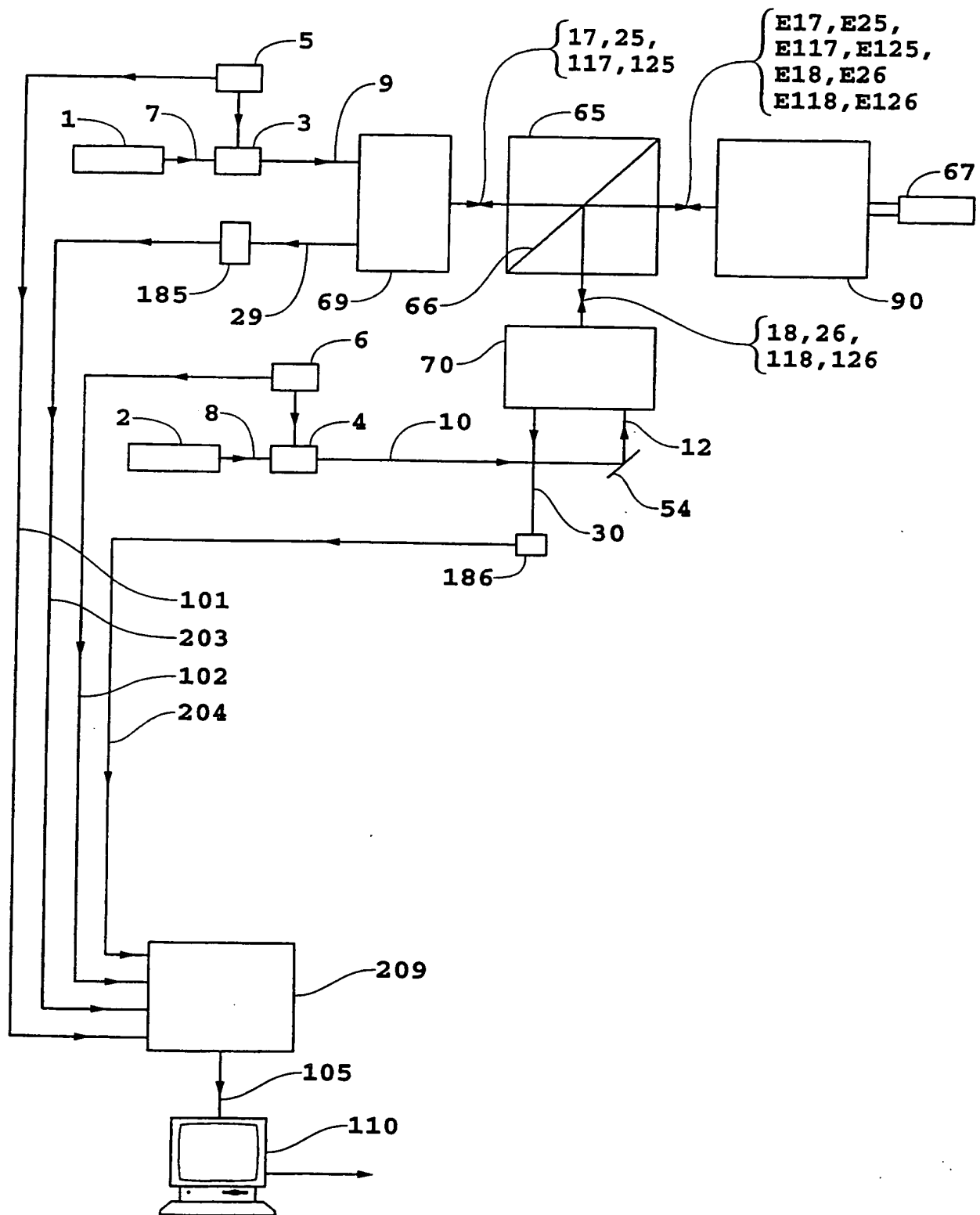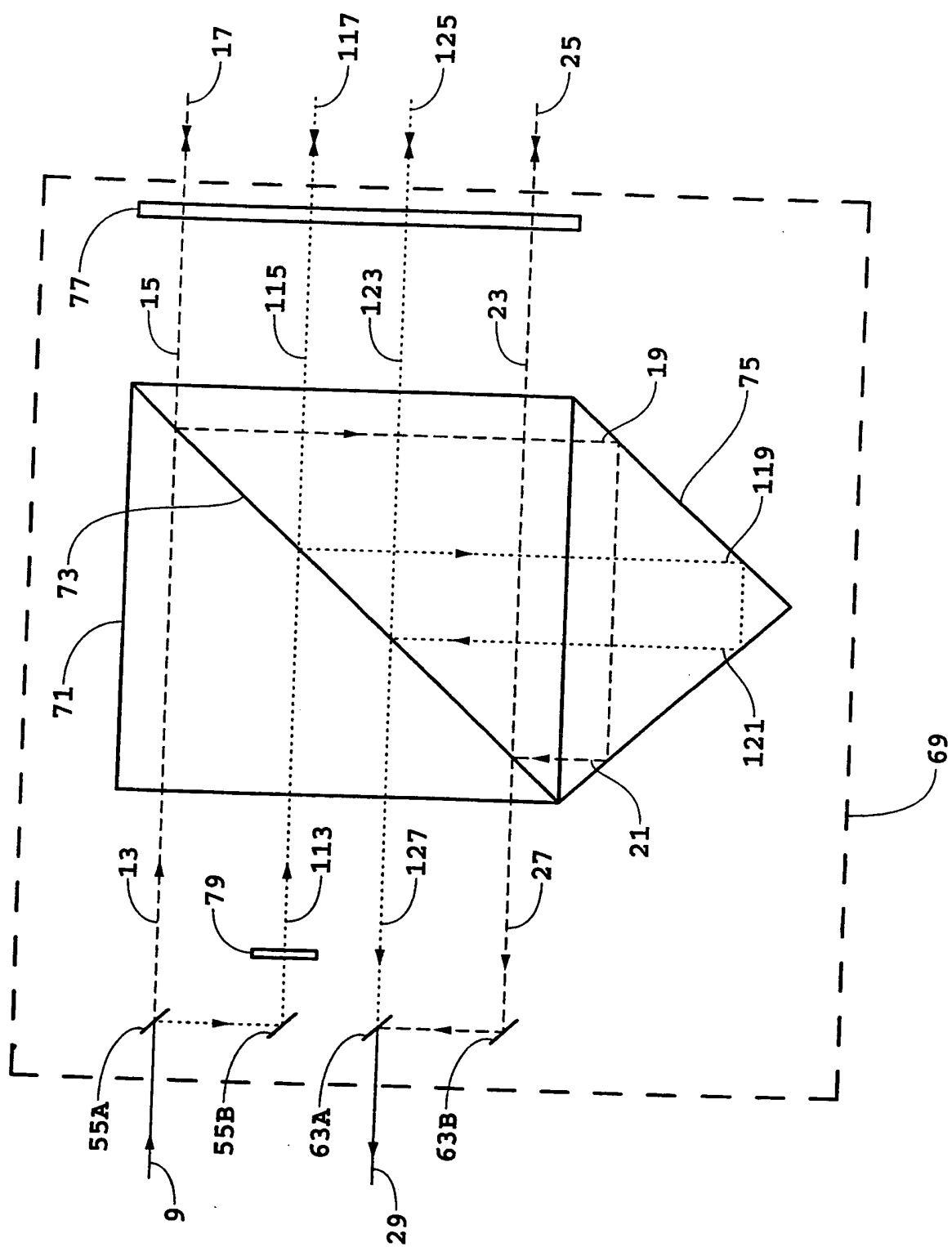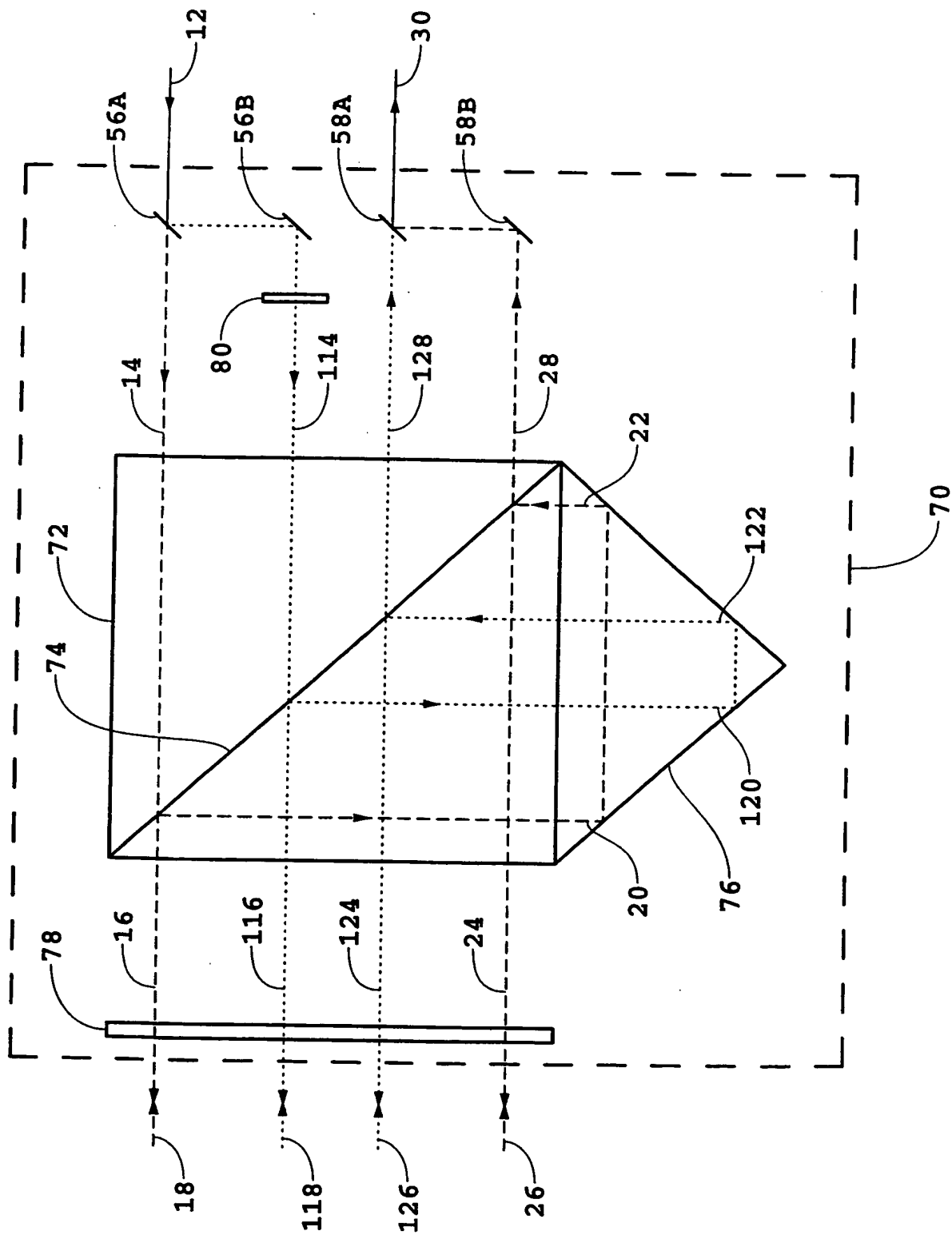
FIG. 1a

FIG. 1b

FIG. 1c

FIG. 1d

FIG. 2a

FIG. 2b

FIG. 2c

FIG. 2d

FIG. 2e

FIG. 2f

11/20

FIG. 3a

$$\left(\frac{l_1}{p_1}\right)\varphi_{1b}$$

$$\left(\frac{l_2}{p_2}\right)\varphi_{2b}$$

FIG. 3b

FIG. 4a

FIG. 4b

FIG. 4c

16/20

FIG. 5

FIG. 6a

```
CIRCUIT DESIGN          ⌐651

         │
         ▼
                              WAFER MANUFACTURE    ⌐653
MASK MANUFACTURE
         ⌐652
         │                          │
         ▼                          ▼

         WAFER PROCESS (PRE-PROCESS)
                                             ⌐654
                    │
                    ▼
         ASSEMBLY PROCESS (POST-PROCESS)
                                             ⌐655
                    │
                    ▼
              INSPECTION
                                             ⌐656
                    │
                    ▼
              SHIPMENT
                                             ⌐657
```

FIG. 6b

QXIDATION PROCESS — 661

CVD — 662

ELECTRODE FORMATION — 663

ION IMPLANTATION — 664

RESIST PROCESS — 665

EXPOSURE — 666

DEVELOPMENT — 667

ETCHING — 668

RESIST SEPARATION — 669

REPEAT
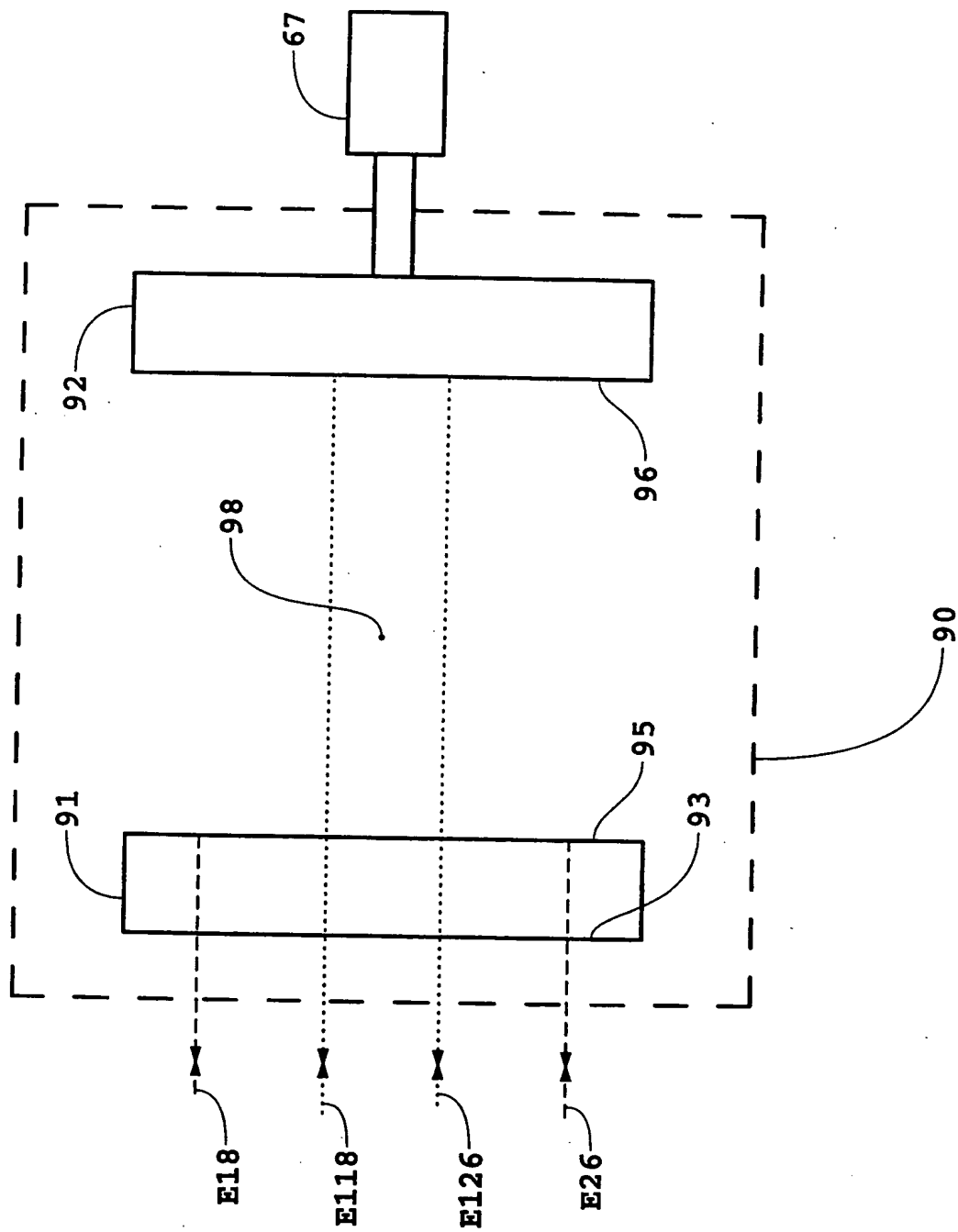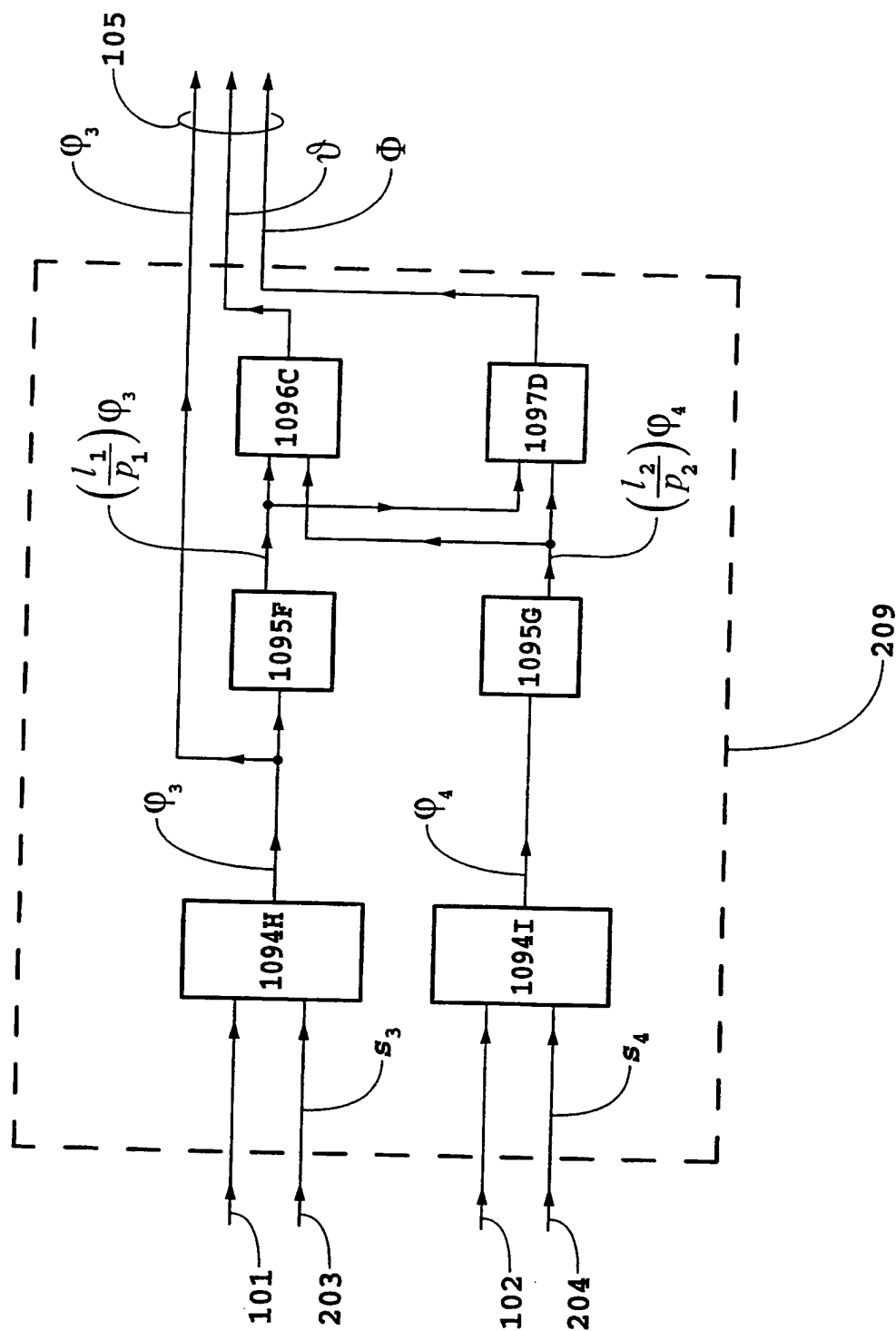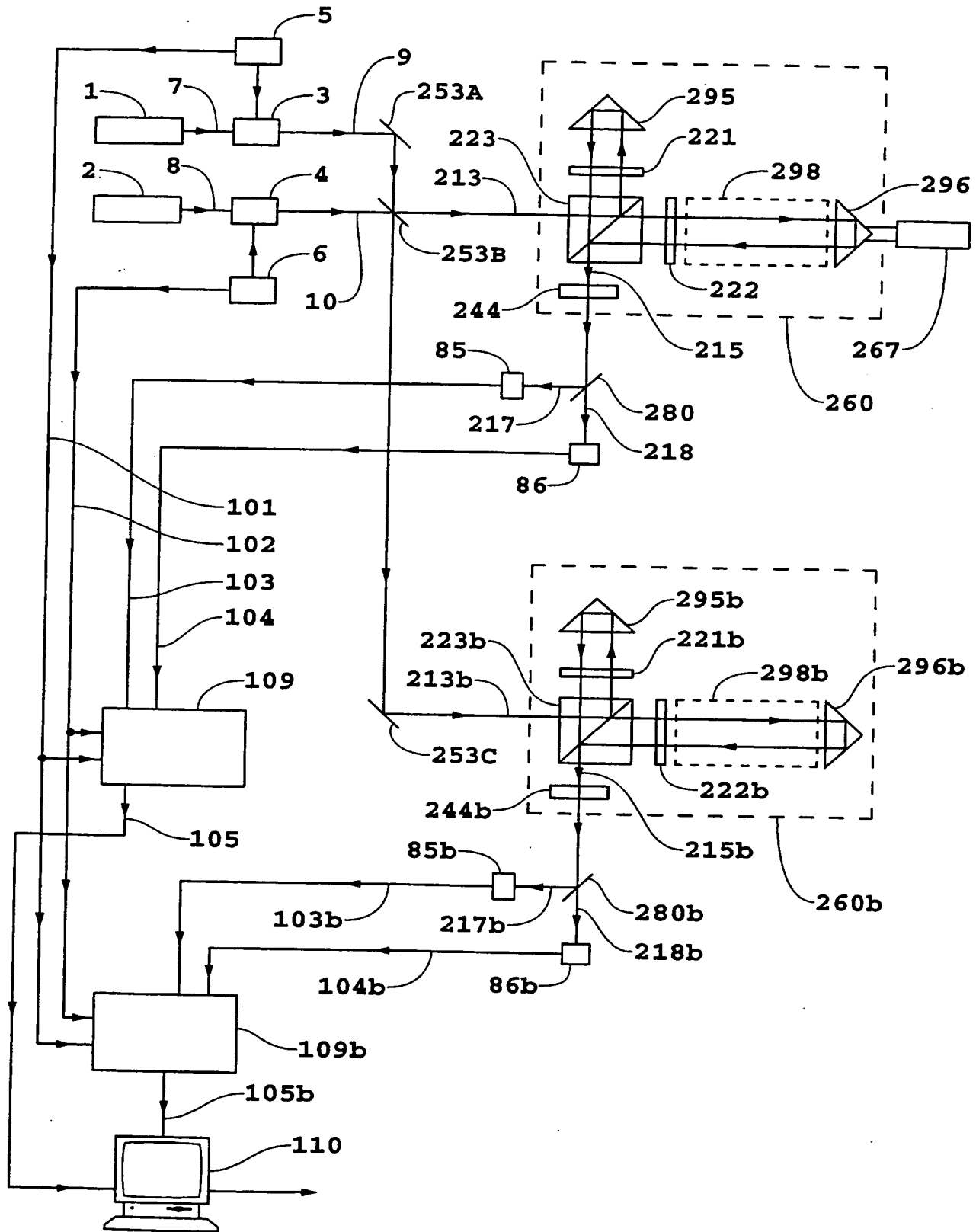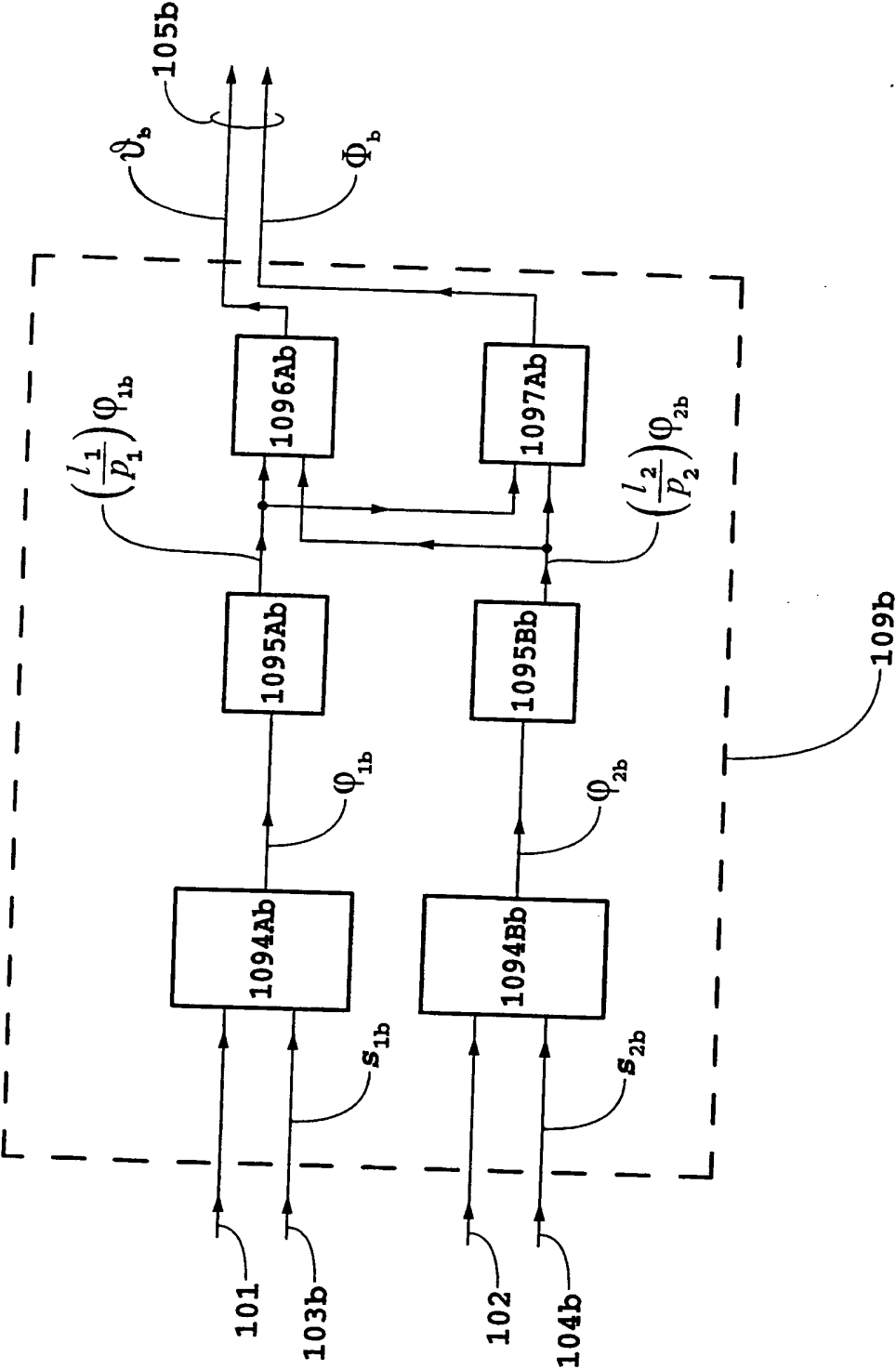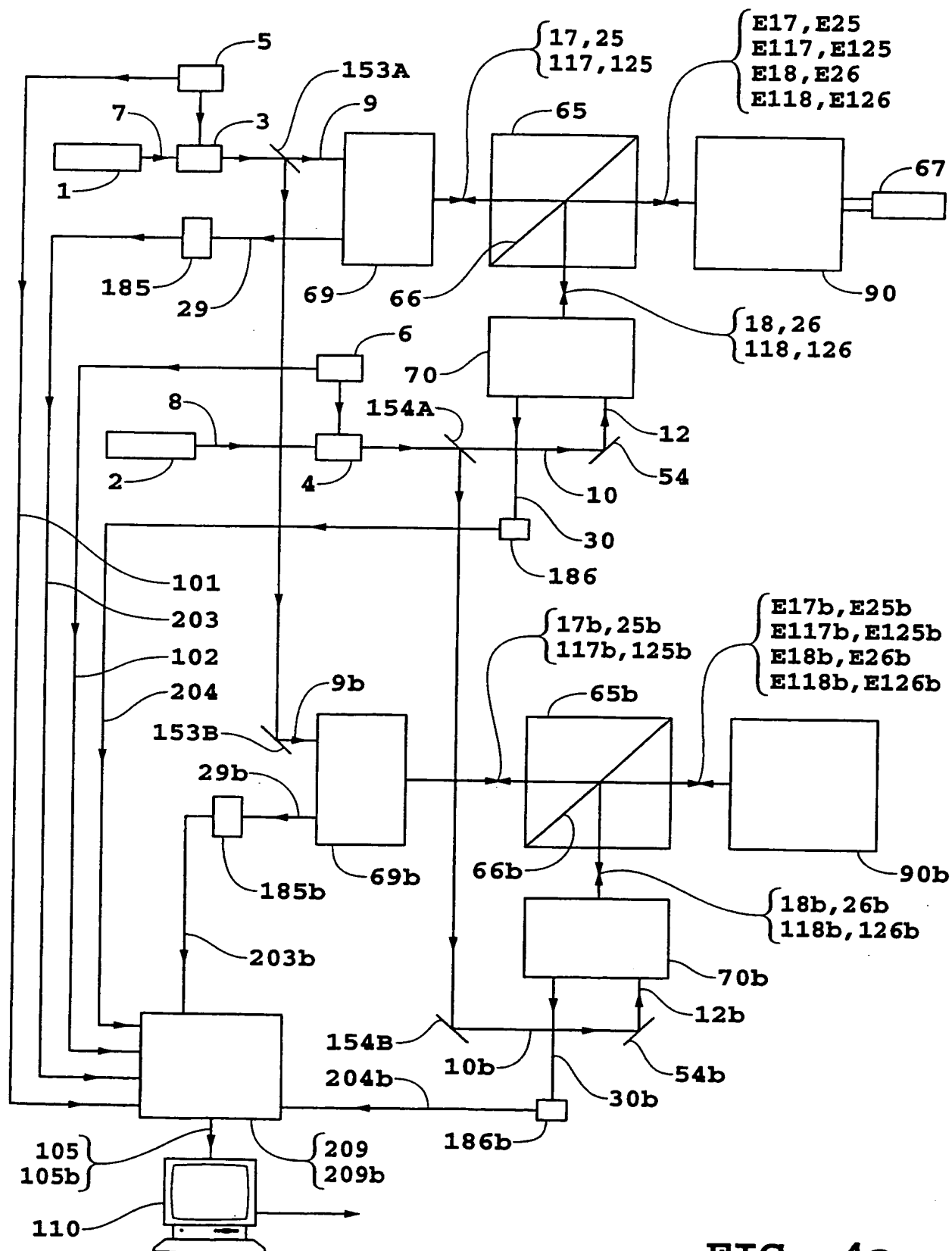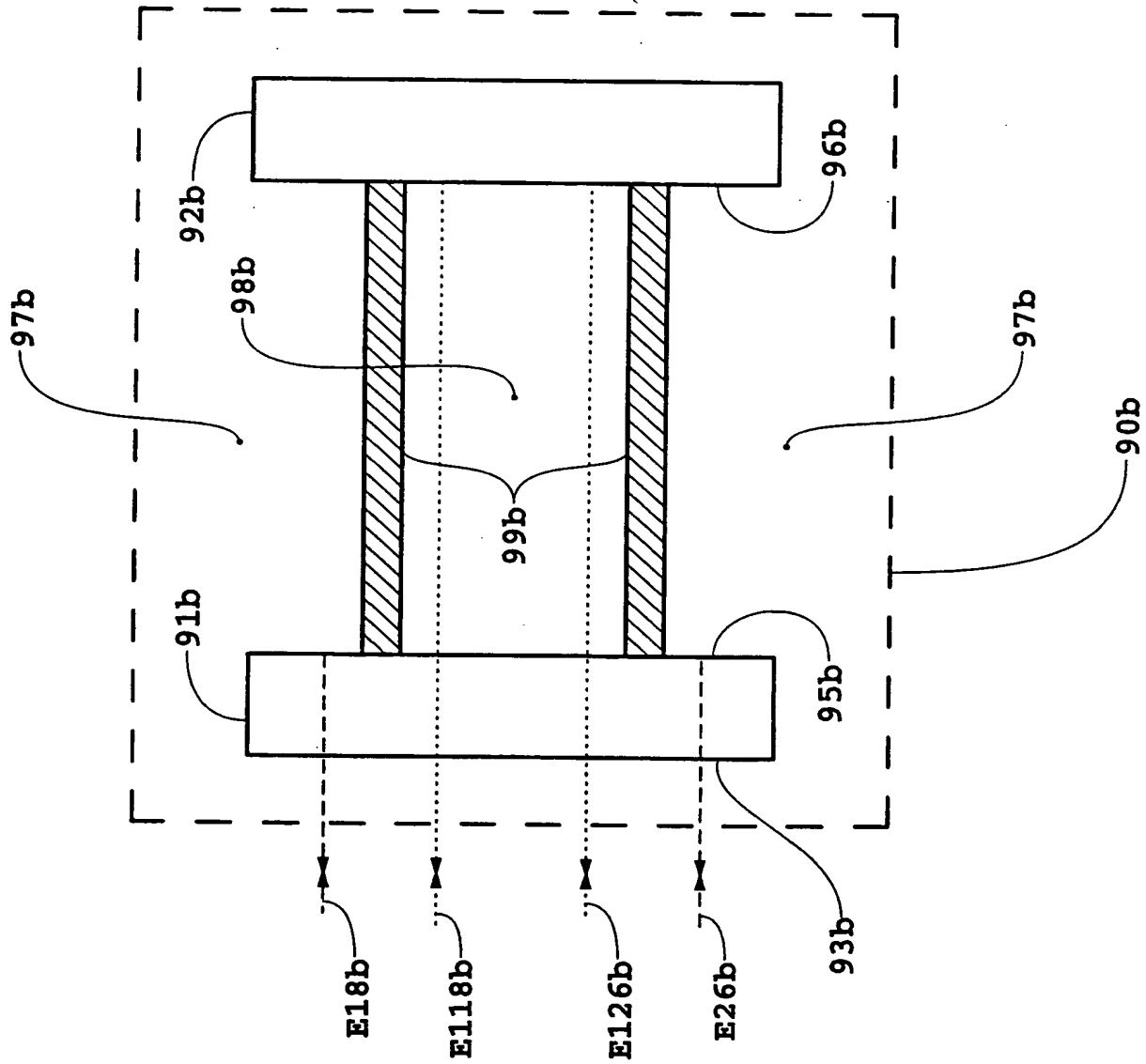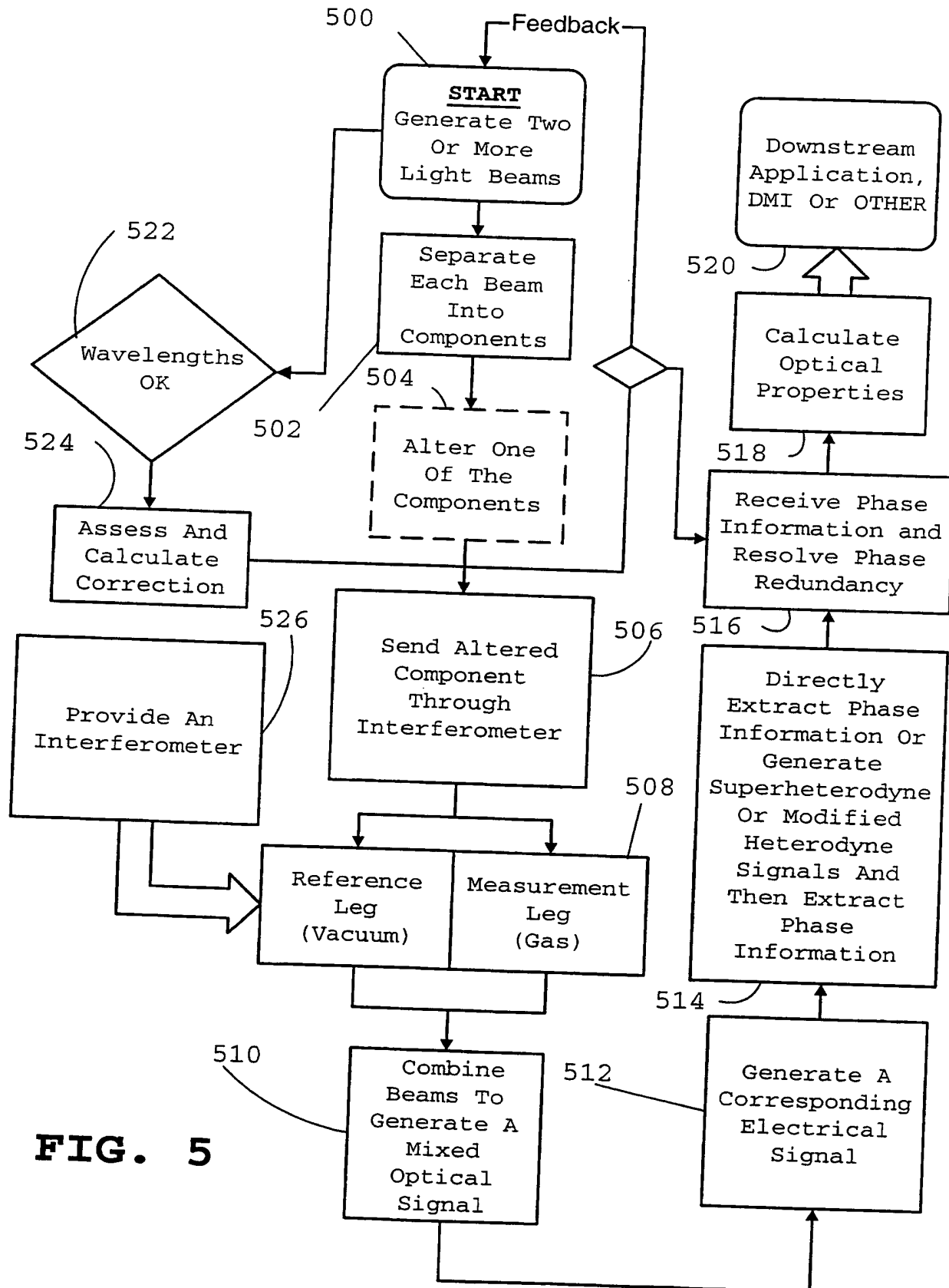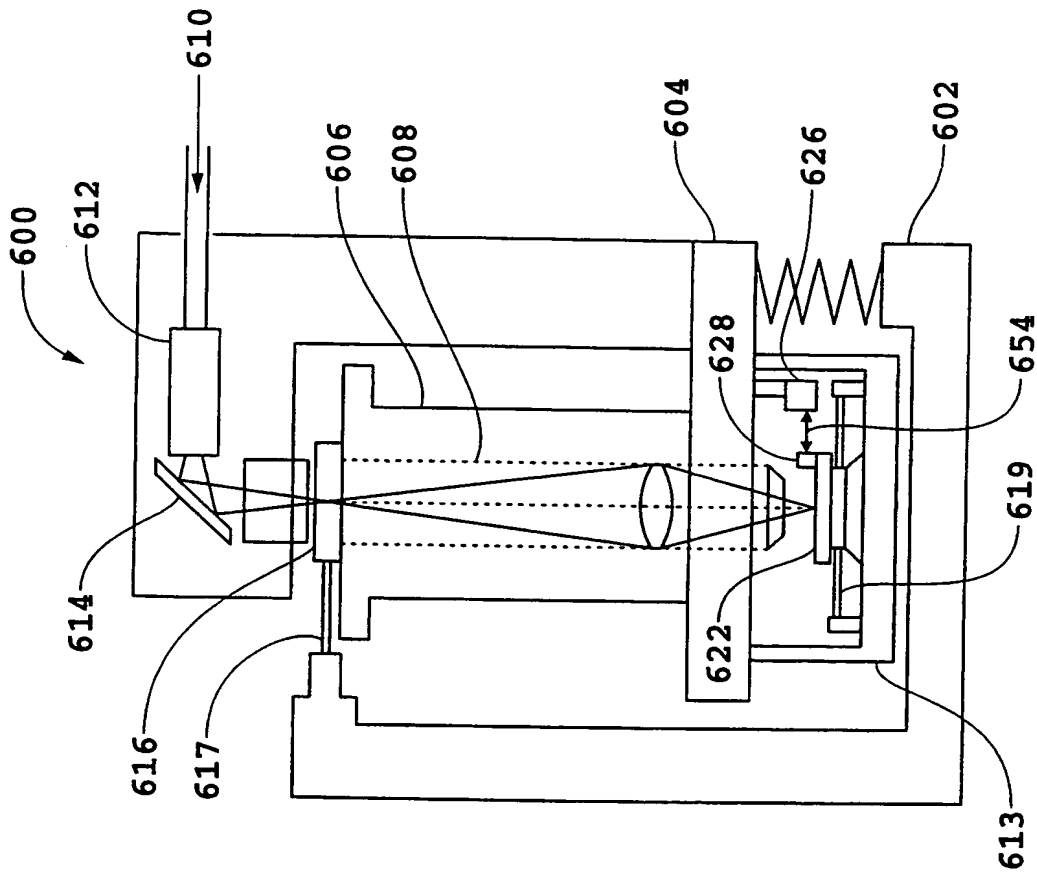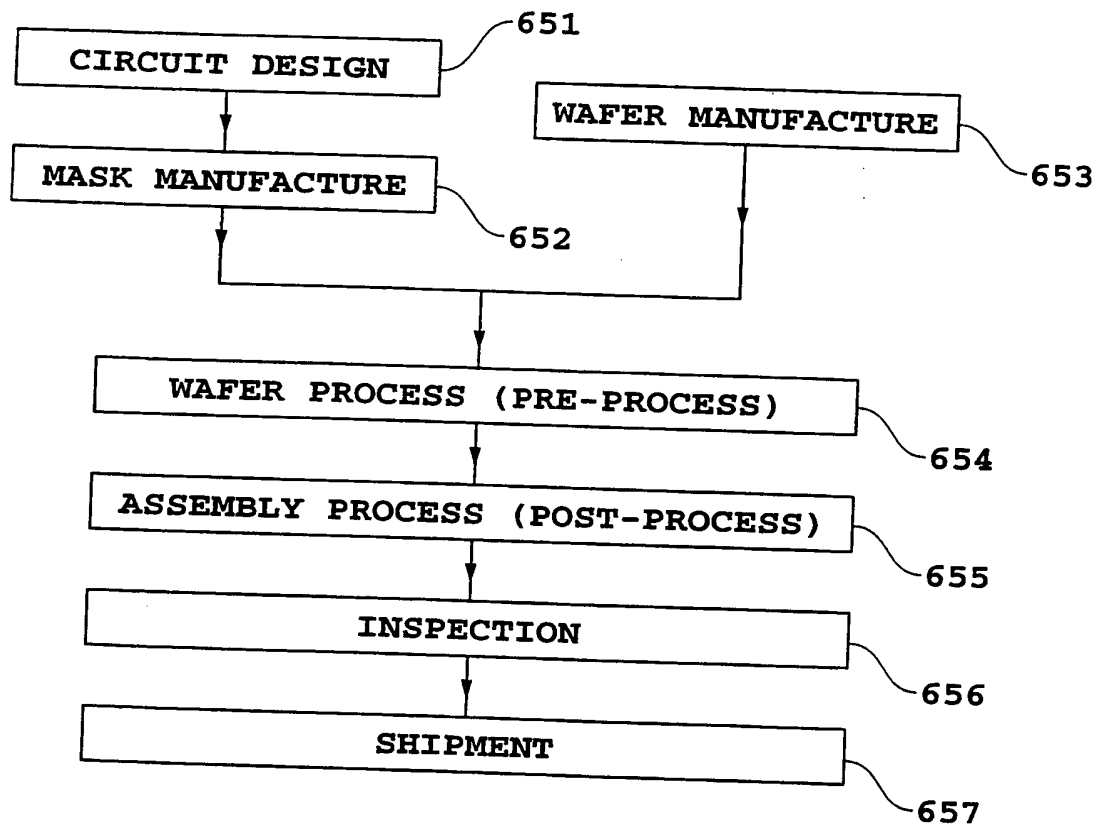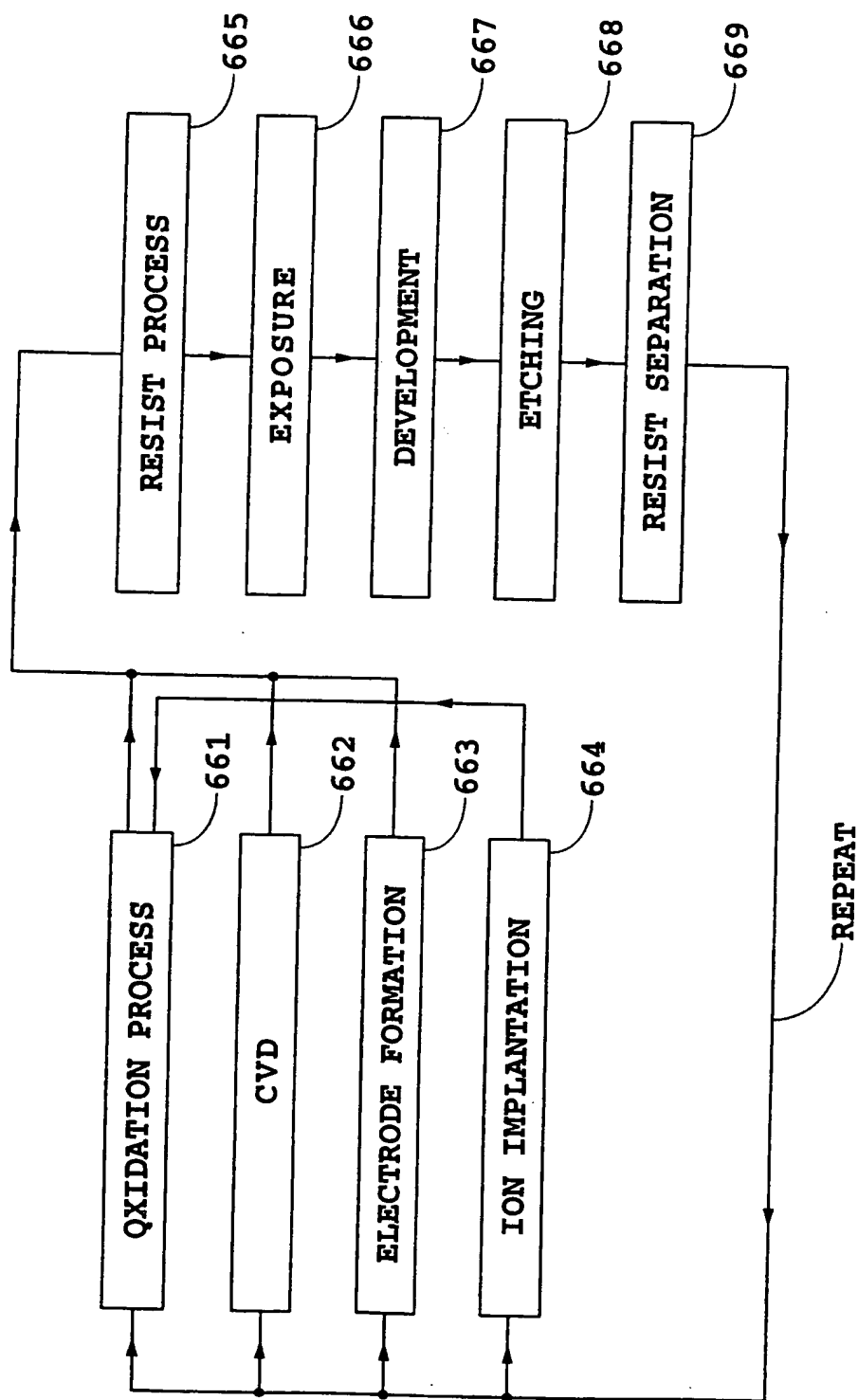
FIG. 6c
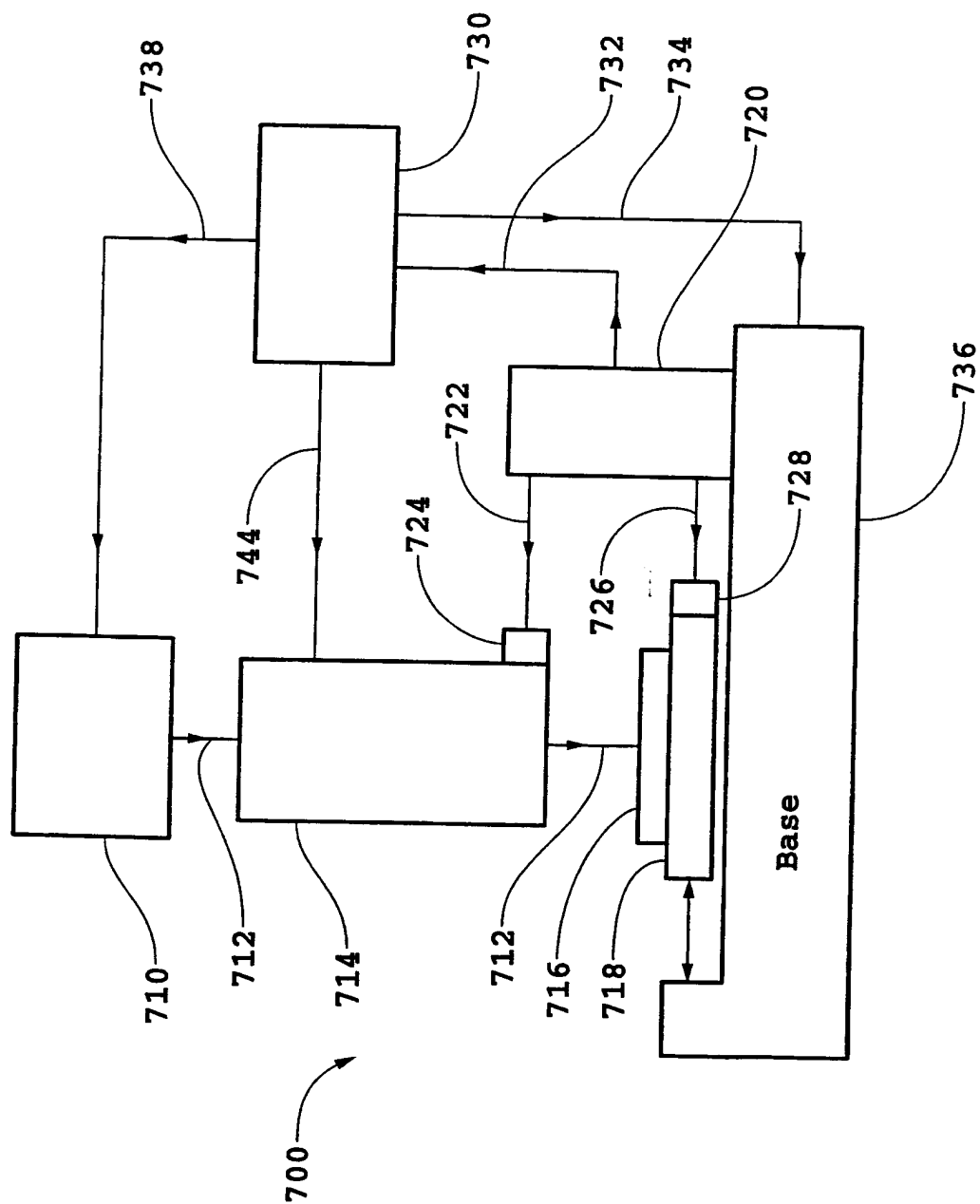
FIG. 7

INTERNATIONAL SEARCH REPORT

A.	CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01B 9/02

US CL : 356/ 349, 351, 358, 361

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/ 349, 351, 358, 361

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

U.S. PTO APS

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

U.S. PTO APS,

search terms: WAVELENGTHS, HARMONIC, GAS, INTERFEROMETER

C.	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ISHIDA, Akira. Two Wavelength Displacement-Measuring Interferometer Using Second-Harmonic Light to Eliminate Air-Turbulence-Induced Errors. Japanese Journal of Physics. March 1989, Vol. 28(3), pages 587-589.	1-72
A	US, A, 5,404,222 (LIS) 04 April 1995 (04/04/95), see entire document.	1-72

☐ Further documents are listed in the continuation of Box C.   ☐   See patent family annex.

*   Special categories of cited documents:

"A"   document defining the general state of the art which is not considered to be of particular relevance

"E"   earlier document published on or after the international filing date

"L"   document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O"   document referring to an oral disclosure, use, exhibition or other means

"P"   document published prior to the international filing date but later than the priority date claimed

"T"   later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X"   document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y"   document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&"   document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 MARCH 1999	**13 APR 1999**
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Authorized officer AMANDA MERLINO
Facsimile No. (703) 305-3230	Telephone No. (703) 305-3488

Form PCT/ISA/210 (second sheet)(July 1992)*

THIS PAGE BLANK (USPTO)